

An Investigation of Volcanic Depressions

Part IV

CASE FILE
COPY

Origin of Hole-in-the-Ground,
a Maar in Central Oregon.

(Geological, geophysical, and energy investigations)

by

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A progress report of work carried out under

NASA Research Grant NGR-38-003-012

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Abstract

Hole-in-the-Ground is a volcanic explosion crater or maar located in Central Oregon on the edge of Fort Rock basin. At the time the crater was formed between 13,500 and 18,000 years ago a lake occupied most of the basin and the site of the eruption was close to the water level near the shore. The crater is now 112 to 156 m. below the original groundlevel and is surrounded by a rim that rises another 35 to 65 m. higher.

The volume of the crater below the original surface is only 60 percent of the volume of the ejecta. The latter contains only 10 percent juvenile basaltic material, mainly sideromelane produced by rapid quenching of the lava. Most of the ejected material is fine grained, but some of the blocks of older rocks reach dimensions of 8 m. The largest blocks are concentrated in four horizons and reached distances of 3.7 km. from the center of the crater. Accretionary lapilli, impact sags, and vesiculated tuffs are well developed.

The crater was formed in a few days or weeks by a series of explosions that were triggered when basaltic magma rose along a northwest-trending fissure and came into contact with abundant groundwater at a depth of 300 to 500 m. below the surface. After the initial explosion, repeated slumping and subsidence along a ring-fault led to intermittent closures of the vent, changes in the supply of groundwater, and repeated accumulations of pressure in the pipe. Four major explosive events resulted from pressures of over 500 bars in the orifice of the vent. Ejection velocities during these periods reached 200 meters per second.

The corresponding pressures and velocities during intervening, less violent stages were in the range of 200 to 250 bars and about 130 meters per second.

The kinetic energy released during the most violent eruptions was approximately 9×10^{20} ergs and the seismic events that must have accompanied these explosions had a magnitude of about 5. Ejecta 10 centimeters in size were thrown to heights of 2 to 3 kilometers and the eruption cloud may have reached 5 kilometers or more. The axis of eruption was slightly inclined toward the southeast; the form of the vent seems to have had a more important influence than wind. Base surges that accompanied some of the explosions left deposits of vesiculated tuff.

The total energy derived from the basaltic magma was of the order of 5.7×10^{23} ergs. Most of this energy went into heating of ground water and the enclosing country rocks; only a small part, possibly a tenth, was released by expansion and vaporization of the water and mechanical processes, such as crushing, acceleration and ejection of debris.

Geophysical measurements indicate a domical intrusion below the crater floor and extending upward as a ring dike around the margins of the crater.

Introduction

Hole-in-the-Ground, a large explosion crater, is situated at the northwestern margin of Fort Rock Basin-Lane County-Central Oregon, approximately 32 km. (20 miles) south of Newberry Caldera (fig. 1).

Although not described in geological literature until 1960, this crater has drawn much attention recently because of its resemblance to certain small lunar craters. Owing to their comparable dimensions, Hole-in-the-Ground offers an excellent example that can be compared with Meteor Crater in Arizona.

Peterson and Groh (1961) were the first to study the crater. They concluded that it was formed by a single or brief series of violent explosions caused by rising magma coming into contact with water-saturated rocks. More recently (1963) these authors have described similar structures in the vicinity of Hole-in-the-Ground and pointed out a common maar-type origin.

The most recent study undertaken by Kim (1968) centers on gravimetric and geomagnetic measurements and their evaluation.

The aim of this study is to give a detailed account of the crater and its genesis and to derive a better understanding of crater-forming processes.

Mapping is based on aerial photographs and a topographic map especially compiled from aerial photographs.

An important obstacle to detailed geological field investigation is, as Peterson and Groh (1961) have already pointed out, a uniform 60 to 70 cm. thick layer of Mazama pumice that covers most of the area. For this reason, our interpretations are based in large part on results of shallow

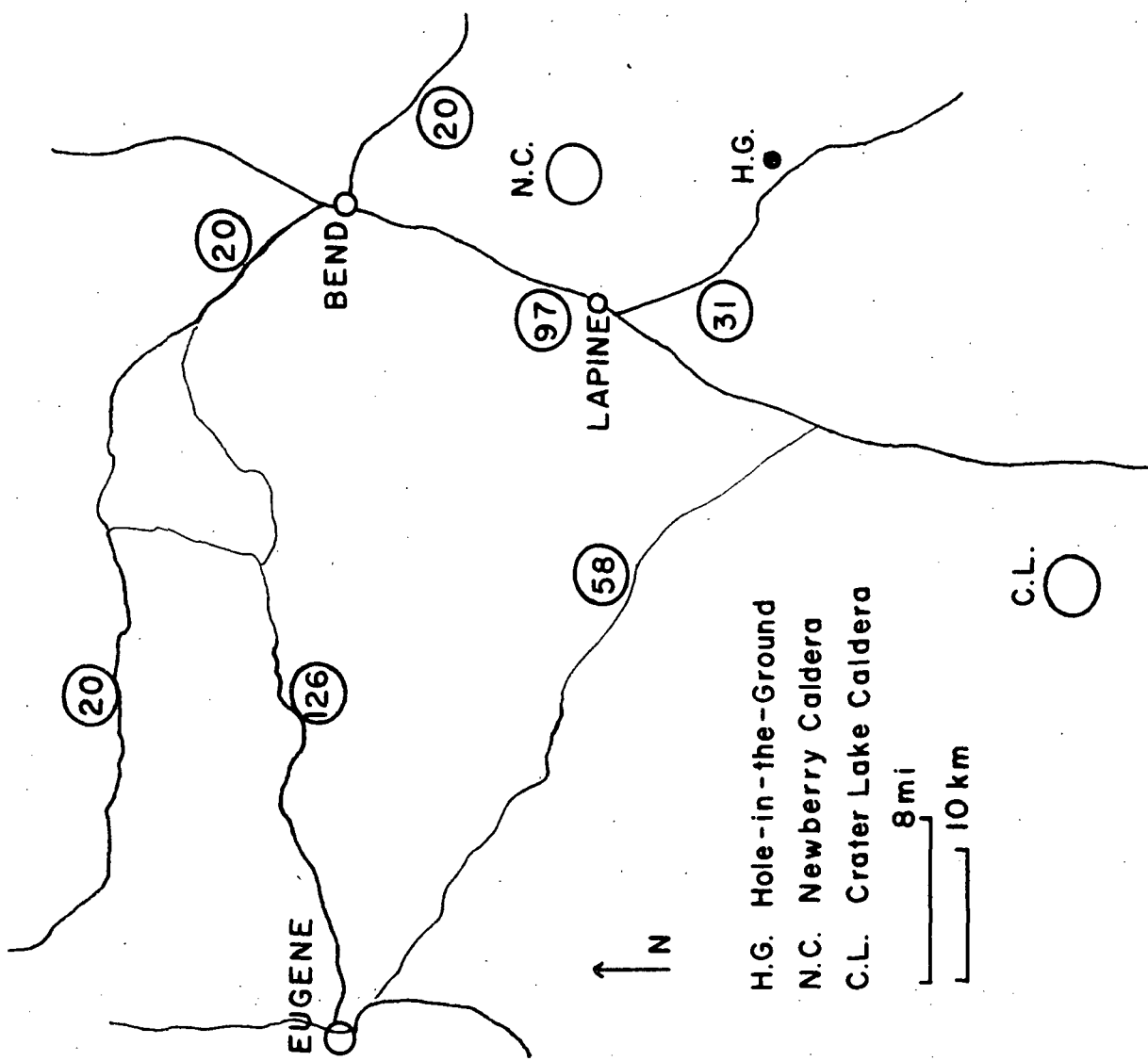


Figure 1. Index map showing location of Hole-in-the-Ground



Figure 2. View of Hole-in-the-Ground from the air. Slopes of Newberry Volcano are in the background.



Figure 3. View of Hole-in-the-Ground looking east. Fort Rock in the background.

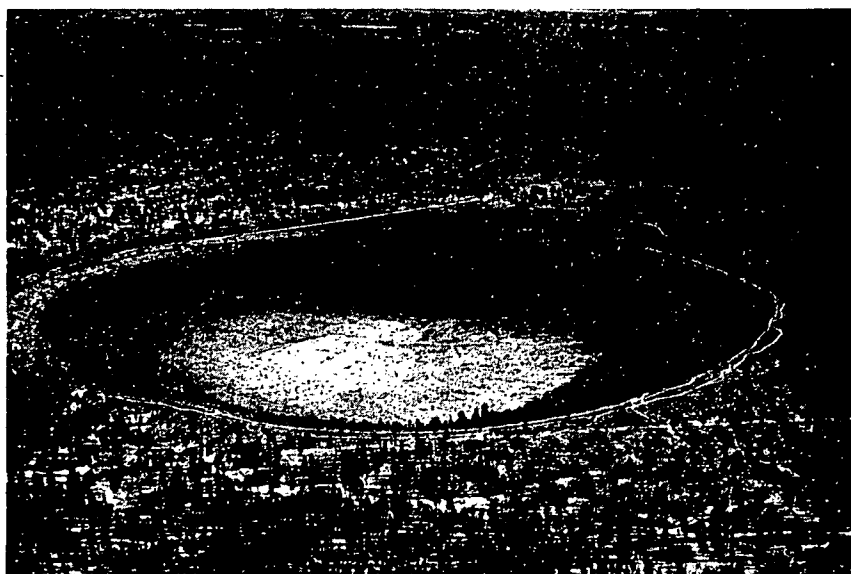


Figure 4. View of Hole-in-the-Ground looking northeast.

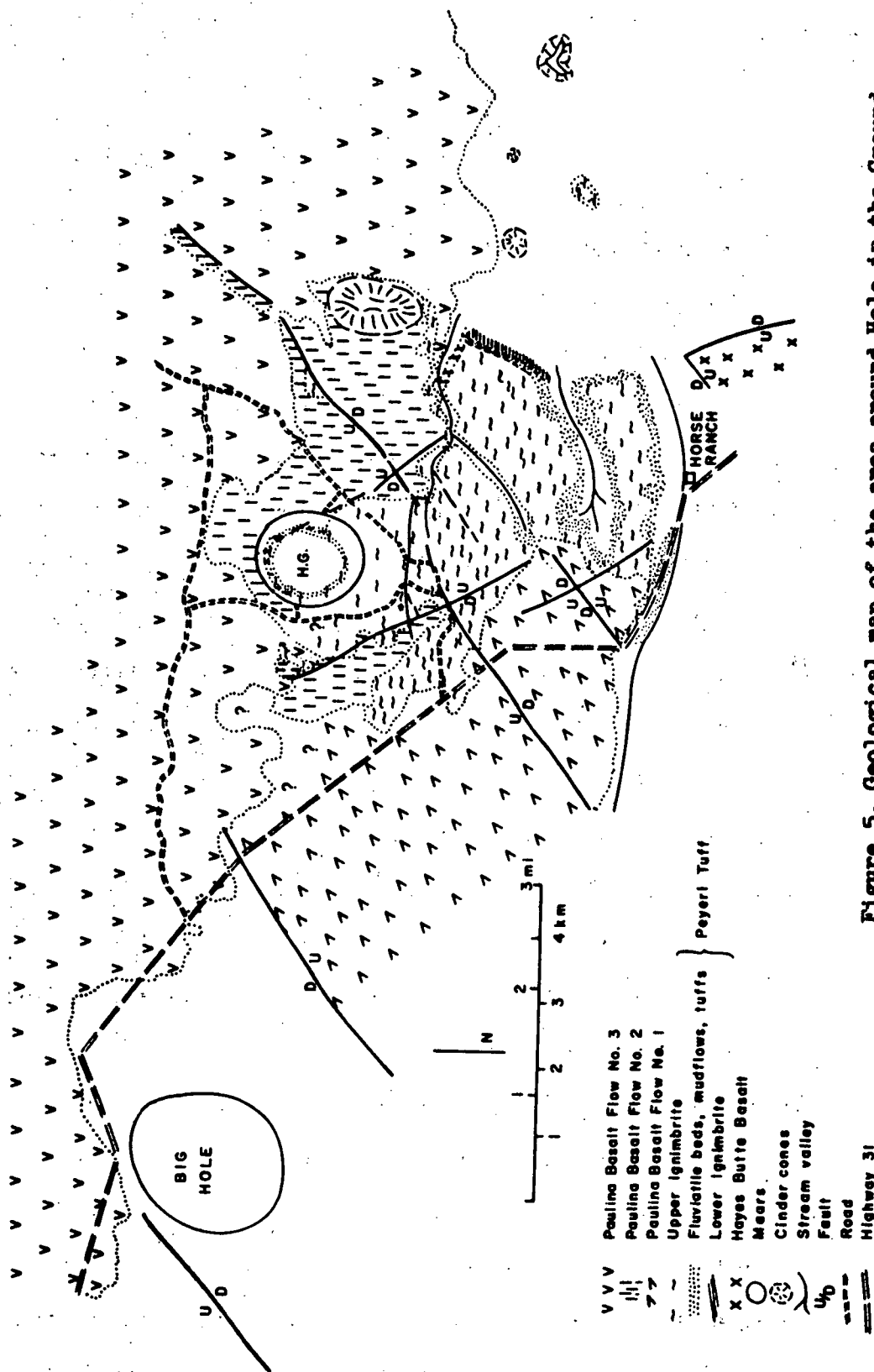


Figure 5. Geological map of the area around Hole-in-the-Ground.

excavations and drill holes, which together with geophysical data, provide essential information on subsurface structure and rock units.

Regional Geology

Picture Rock Basalt

The stratigraphy of the Fort Rock Basin has been compiled and correlated from scattered outcrops and numerous well logs (Hampton, 1964). The rocks range in age from Pliocene to Recent and consist almost entirely of tuffs, lavas and volcanic sediments. A generalized stratigraphic column is shown in fig. 6. The oldest rocks known in the Fort Rock Basin were described by Hampton (1964) as lava-flows and interbedded tuffs and sediments of the Picture Rock basalt. Lava-flows of this unit are dark grey, blue-grey or dark green, 3 to 16 m. thick and consist of a glassy or microcrystalline groundmass containing olivine-crystals up to 2 mm. and plagioclase crystals up to 6 mm. The interbedded pyroclastic beds and sediments are composed of stratified basaltic tuffs, pumiceous conglomerates and sandstones. The thickness of this unit may exceed 330 m.; Hampton (1964) tentatively assigns it an age of early Pliocene. The nearest exposures of Picture Rock basalt are 38 km. to southeast of Hole-in-the-Ground at Silver Lake. It is not known whether this unit is present at depth in the Hole-in-the-Ground area.

Volcanic rocks of intermediate composition unconformably overlay Picture Rock basalt at Cougar Mountain and Horning Bend (respectively 19 km. southeast and 24 km. east of Hole-in-the-Ground). The volcanic cone at Horning Bend is described by Hampton (1964) as being composed of a fine-grained blue-grey to buff andesite, whereas Cougar Mountain is composed of a glassy to fine-grained rock, probably rhyodacite. The

Name	Lithologic Characters	Thickness
Paulina Basalt	Basaltic lavas	0-30m
Peyrer Tuff	Tuffs, ignimbrites & tuffaceous sediments	0-130m
Hayes Butte Basalt	Basaltic lavas	20-450m
Fort Rock Formation	Tuffs, diatomite beds, basaltic agglomerates & basaltic lavas	330m
Volcanic Rocks of intermediate composition	Andesitic and rhyodacitic lavas	0-330m
Picture Rock Basalt	Basaltic lavas with interbedded tuffs and sediments	>330m

Figure 6. Stratigraphic sequence of the Fort Rock Basin after Hamilton (1964)

maximum thickness of these beds exceeds 330 m. at the central part of both cones, but gradually diminishes laterally. Hampton (1964) estimates their age to be middle Pliocene. 16 km. north of Hole-in-the-Ground intermediate rocks occur at Indian Butte. According to Williams (1957) porphyritic pyroxene andesite and andesitic basalt flows strike $165-170^{\circ}$ southeast and dip both to the west and east. These flows are presumably pre-Pliocene in age. It is not known whether lava-flows at any of these three places reached the area of Hole-in-the-Ground nor whether any vents discharging rocks of similar composition and age occur at depth near Hole-in-the-Ground.

The Fort Rock Formation

Unconformably overlying the volcanic rocks of intermediate composition and the Picture Rock basalt are, in order of abundance, tuffs, diatomite, basaltic agglomerate and basaltic lava, collectively named the Fort Rock Formation. The tuffs are mainly basaltic lapilli-tuffs and contain interbedded diatomite. Near eruptive centers the tuffs become coarse and change finally into basaltic agglomerates. Interbedded basalt-flows are of dark grey color and about 2 to 5 m. thick. On the basis of stratigraphic position, lithology and fossil evidence, the Fort Rock Formation is assigned a middle to late Pliocene age. Its total thickness, as indicated by well logs, is about 330 m. This rock-unit can be assumed to extend to Hole-in-the-Ground at depth.

The Hayes Butte basalt lava flows which compose the next higher unit are very widespread in the Fort Rock Basin. Hampton (1964) describes the texture of the light to dark grey basalts as varying from diktytaxitic lava to frothy scoria or dense glassy ropy lava. Individual flows which range in thickness from 3-10 m. display a thin scoriaceous glassy or brecciated base, a dense fine-grained center, and a vesicular to rubbly

top. Most of the lavas are basaltic, but some of the light grey and glassy rocks may approach andesitic compositions. At most exposures the unit is formed by one or two lavas, their combined thickness seldom exceeding 35 m. The Hayes Butte lavas were erupted from centralized areas, mostly along a north-northwest trending fault zone. Some of the cones are as much as 6 km. across the base and up to 450 m. high, but most are much smaller. Hampton (1964) tentatively assigned to the Hayes Butte basalt unit a late Pliocene to early Pleistocene age. The nearest lava-flow of Hayes Butte basalt occurs about 6 km. southeast of Hole-in-the-Ground and 1.5 km. east of Horse Ranch. It is composed of a dark grey basalt containing phenocrysts of plagioclase and olivine up to half a centimeter long and olivine.

Further to the north between Fort Rock and Hole-in-the-Ground several scoria cones have interlayered or capping lava-flows; one is only $3\frac{1}{2}$ km. east-southeast of Hole-in-the-Ground on a north-northeast trending fissure. Hampton believes some of these cones can be assigned to the Hayes Butte basalt unit. Since rocks of this unit occur only a few kilometers away from Hole-in-the-Ground it is quite possible that this unit extends at depth to the area of Hole-in-the-Ground.

Southeast of Hole-in-the-Ground Hayes Butte basalt is unconformably overlain by a sequence of tuffs, ignimbrites and tuffaceous sediments that Hampton (1964) named Peyerl Tuff. The upper part of this unit is well exposed in a road cut 5 km. south of Hole-in-the-Ground in State Highway 31 (sec. 31; T 25 S:R 13 E) and is well described by Hampton (1964, p. B12-B13). Only a brief description need be given. The sequence is predominantly composed of waterlain tuffs, tuffaceous sandstones and mud-flows. Yellowish white to dark grey pumice fragments with diameters up to 30-40 cm. are principal components of several horizons,

whereas in others round to angular pebbles of basalt form a major component. The top of the sequence is formed by an ignimbrite which extends over large areas south of Hole-in-the-Ground. The bottom part of this ignimbrite (about 1 m.) is composed of grey-yellow pumice which grades upward into platy yellowish to pink welded tuff. This welded tuff crops out in the crater wall of Hole-in-the-Ground and is described below.

The upper part of the Peyerl Tuff unit also crops out 5 km. southeast of Hole-in-the-Ground at an erosional escarpment where crossed by a country road in sec. 28, T. 25 S., R. 13 E. This section, which is also described by Hampton (1964), contains a second ignimbrite about 40 m. below the top of the sequence. This ignimbrite is at least 8 m. thick, its base not being exposed. It is chocolate brown to grey brown and contains angular fragments of lava, black pumice and lumps of frothy glass as large as 3 cm. in diameter.

The total thickness of the Peyerl Tuff is about 130 m. The lower third, which is known only from a well at Horse Ranch, consists of gravels, clay, tuffs, and basalts (?) (Hampton 1964). Because of its stratigraphic position the Peyerl Tuff unit is believed to be late Pliocene or early Pleistocene in age. Since a sample of the upper ignimbrite was found to be magnetically reversed the whole unit must be older than 700,000 years.

The next younger rock unit, named Paulina Basalt by Hampton (1964), forms the main unit beneath the surface at the northern margin of Fort Rock Basin. It is composed of basalt flows discharged from several eruptive centers to the north and northwest. Near Hole-in-the-Ground three different flows can be distinguished. Flow No. 1 southwest of Hole-in-the-Ground was presumably erupted 20 km. west-southwest of Hole-in-the-Ground in the area of Stams Mt. and Bald Mt. and flowed to

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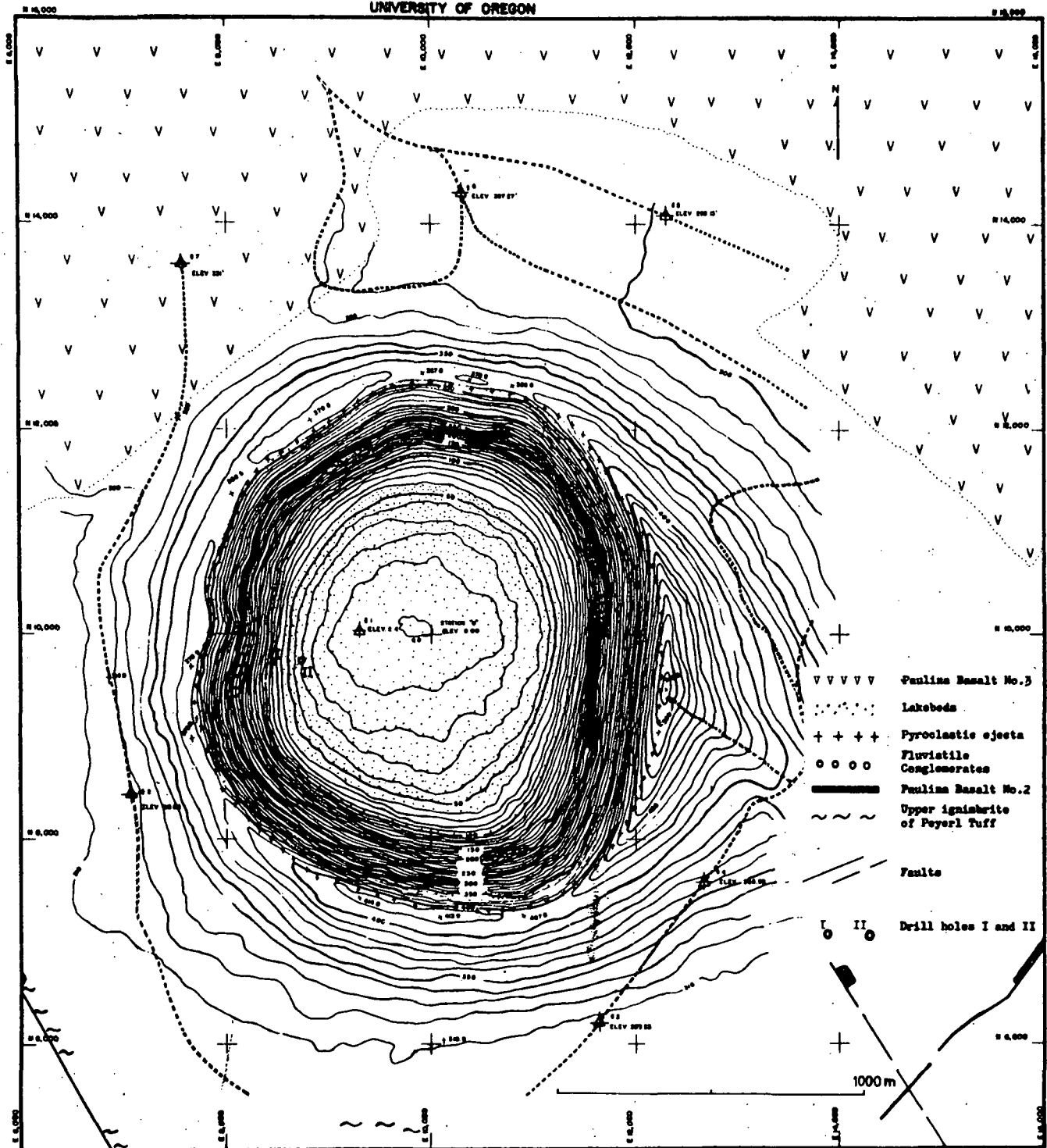


Figure 7. Topographic and geologic map of Hole-in-the-Ground. Contour interval is ten feet. Field control by J. W. Hawthorne.

the northeast without reaching the area of Hole-in-the-Ground. Outcrops of this flow can be found along Highway 31 west and southwest of Hole-in-the-Ground.

Flow No. 2 is exposed in the crater wall of Hole-in-the-Ground and in various areas west and east of the crater, but is mostly covered by the eruption products of Hole-in-the-Ground and a younger lava (Flow No. 3). From its known extent (fig. 5) it is assumed that this lava was erupted somewhere north of Hole-in-the-Ground and had its flow-front in the area of the crater. Hole-in-the-Ground itself is situated at the margin of a concave lobe between two different flow tongues, and only the northern part of the crater rim is underlain by this lava-flow. Its thickness varies between 30 cm. and 18 m. Both flows No. 1 and No. 2 are reversed in their magnetic orientation and thus older than 700,000 years. Paulina Basalt No. 3 overlies flow 2 and is derived from a fissure northwest of Indian Butte on the upper slope of Newberry volcano. Its flow front is situated north and east of Hole-in-the-Ground where it forms a concave lobe against the crater rim. It is clear that Hole-in-the-Ground is older than flow No. 3 as has already been pointed out by Peterson and Groh (1961, fig. 3). This youngest flow covers three faults offsetting Paulina Basalt flows No. 1 and 2, so there was probably a considerable time interval between the second and third flows. Fresh surface structures on flow 3 and the poorly preserved surface structures of flows No. 1 and 2 also point out a long interval.

Large areas of Fort Rock Basin are covered by a thin layer of lakebeds, terrace and delta deposits of a pluvial lake. The highest lake level recognized by Hampton (1964) was about 1380 m. (4500') in elevation and thus could not have reached Hole-in-the-Ground where the immediate surrounding area is above 1410 m. (4600').

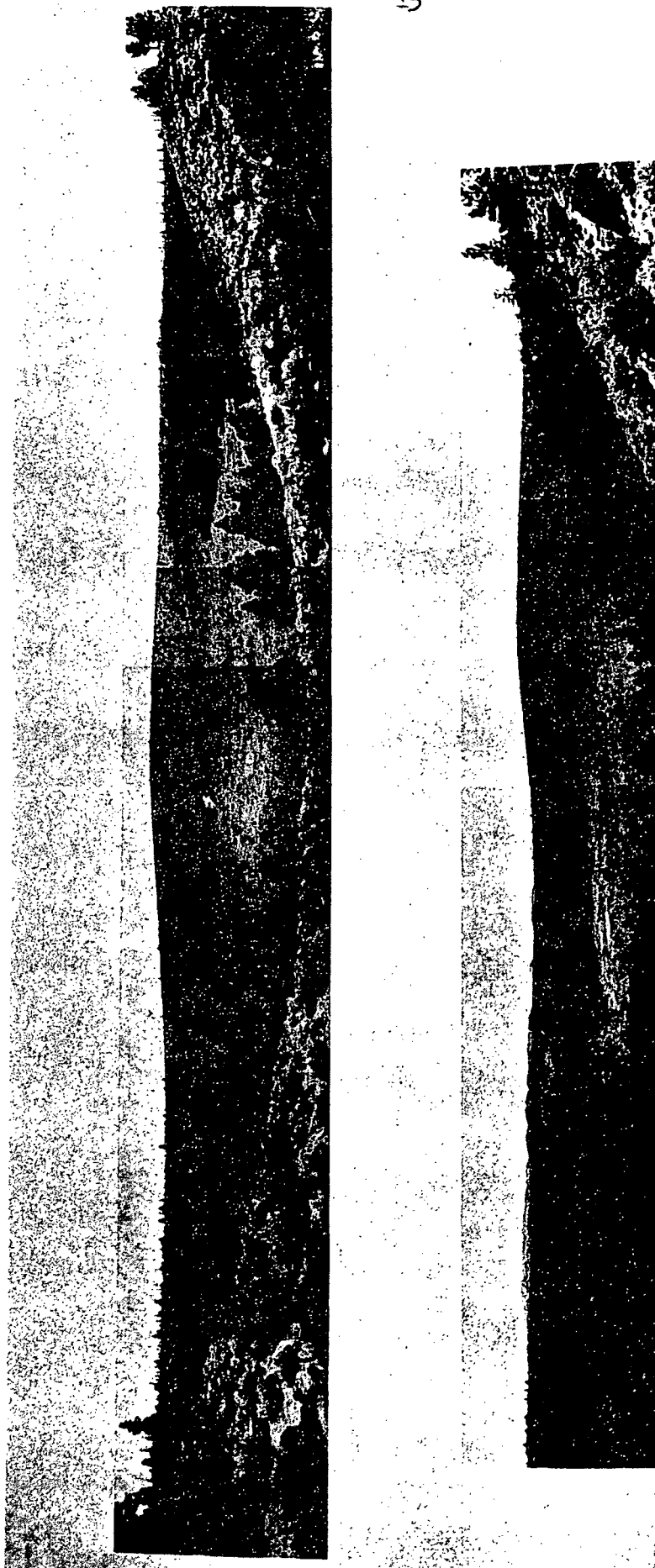


Figure 8. Composite photographs of Hole-in-the-Ground looking east (upper view) and north (lower view).

A later lake level reached an elevation of 1340 m. (4390') at Fort Rock somewhat earlier than 13,000 years ago when a cave formed by the wave action of this lake was inhabited by early man (personal communication, Bedwell (1968)).

Even younger are the airborne deposits of Mazama pumice which covered the area of Hole-in-the-Ground and its vicinity with a blanket 60-70 cm. thick. Latest C¹⁴ data (Bedwell, personal communication, 1968) indicate that the Mazama pumice of the Fort Rock area was deposited about 7,000 years ago.

Structure

Three sets of normal faults have been observed near Hole-in-the-Ground. South of Hole-in-the-Ground and northwest of Silver Lake, northwest-southeast trending faults have displacements of as much as 100 m. Further to the north they trend more to the north-northwest and north-northeast. Still further to the north near Hole-in-the-Ground northeast-southwest trending faults with displacements up to 15 m. are frequently accompanied by a few that trend northwest-southeast. The latest displacement along the faults near Hole-in-the-Ground is younger than Paulina basalts 1 and 2 and older than the formation of Hole-in-the-Ground, the eruption products of which are not affected by any fault which cuts the Paulina Basalt.

Hydrogeology

Today the climate of Fort Rock Basin is semi-arid, its annual precipitation being less than 25 cm. Several small stream valleys south of Hole-in-the-Ground are almost dry most of the year, but had a higher water flow

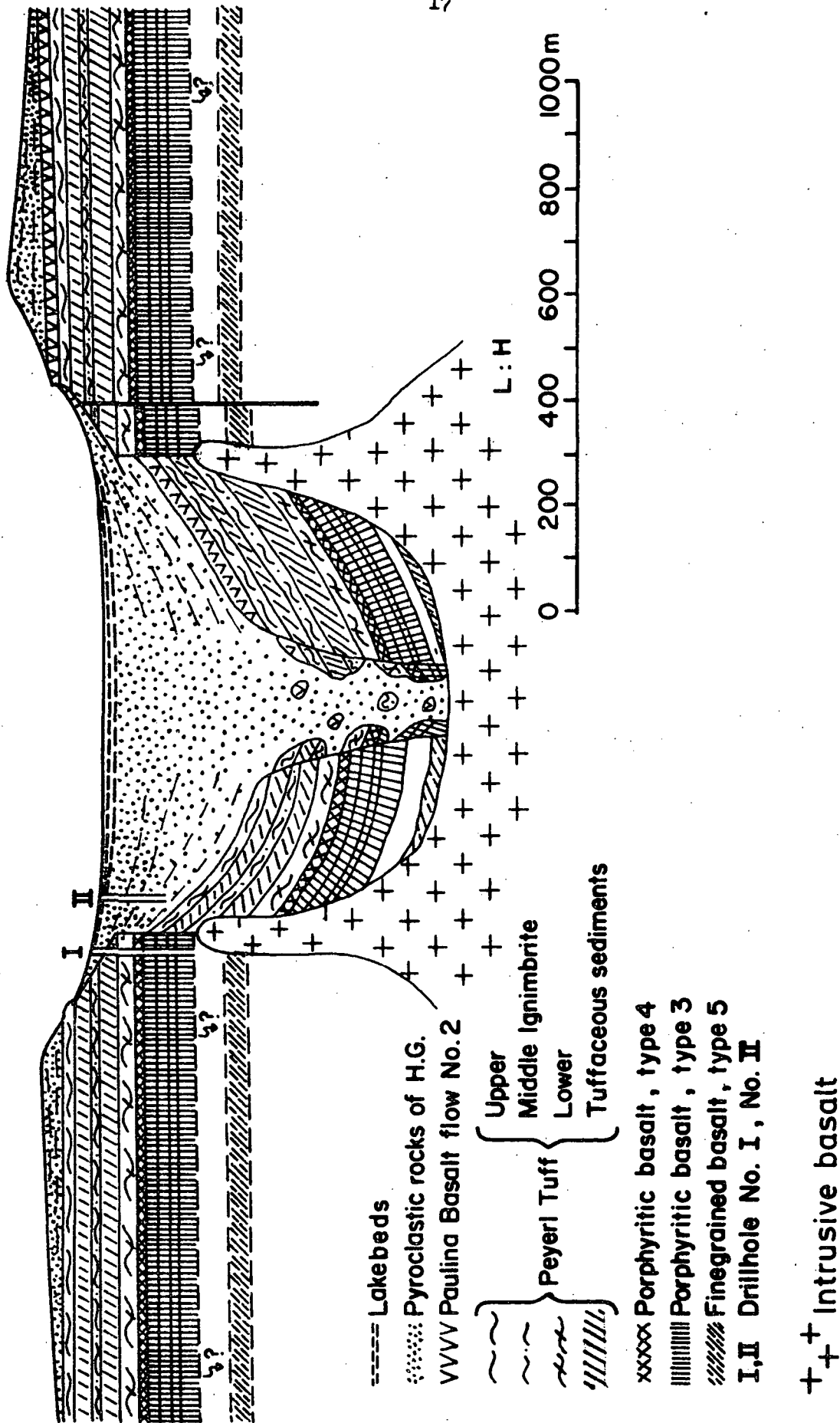


Figure 9. Geologic section through Hole-in-the-Ground based on surface exposures, drill holes and geophysical data.

in pluvial times. Nevertheless the regional water-table in the Fort Rock area is still only a few meters below the surface (Newcomb, 1952). Around the margins of Hole-in-the-Ground the surface of the water-table is more than 50 m. below the surface, but it nearly reaches the floor of Hole-in-the-Ground Crater. Lake beds and terrace deposits at various elevations indicate that during the last pluvial period a lake of varying depth occupied large areas of Fort Rock Basin. Some of the stream valleys south of Hole-in-the-Ground must have fed this lake. As already mentioned one of the last high lake levels (1340 m. 4390') was reached more than 13,000 years ago.

Geology of the Hole-in-the-Ground Crater

Hole-in-the-Ground is a flat-floored, nearly circular crater with an average diameter of 1530 m. (max. 1640 m., min. 1410 m.) and an average depth below the rim of 134 m. (max. 156.5 m., min. 112 m.). Its depth to diameter ratio is therefore about 1:11. During formation of the crater a rim with a maximum height of 83.4 m. was built around all sides. The lowest point of the crater floor is about 82 m. below the original ground surface. The inner slope has a maximum inclination of 27° , the outer having only 5° .

Mazama pumice covers the entire crater except for a small area in the very center and most of the inner slopes. The most prominent exposures occur between 52 and 82.5 m. in the west, north and east wall of the crater. Above the 82.5 meter level exposures are confined to a few horizons and except for the uppermost one just below the rim, they are inconspicuous.

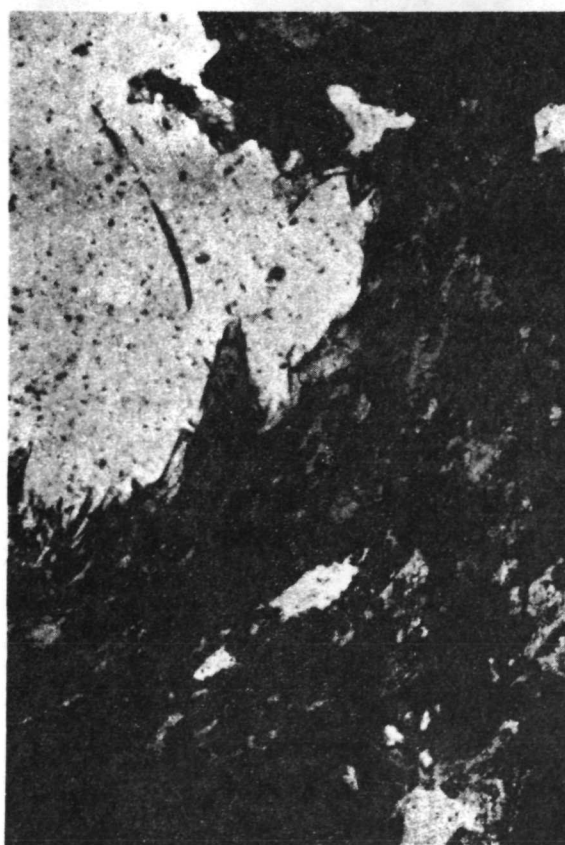
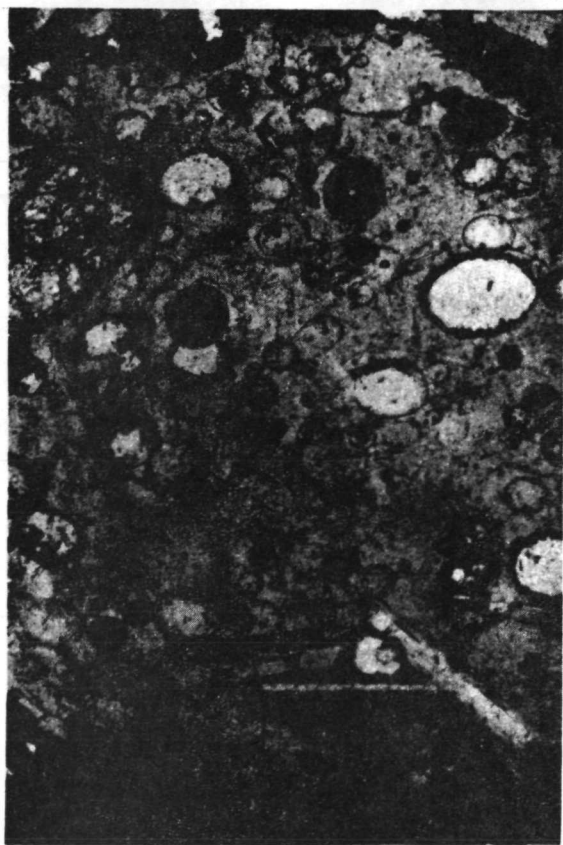
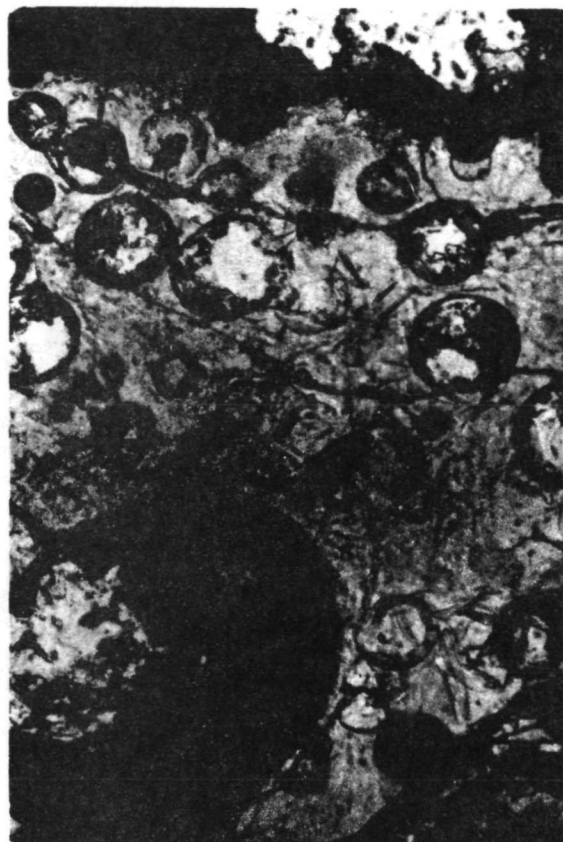


Figure 10. Photomicrographs of juvenile lapilli. Width of field is about 1 mm. Note the clear basaltic glass and elongated bubbles.

Large talus blocks occur between the 45 and 82.5 m. levels. Other large blocks are scattered around the upper half of the crater wall, on the rim. Only a few can be seen on the crater's outer slopes, but this may be partly because of the thick blanket of Mazama pumice.

The crater floor and walls are covered by sagebrush and the south and southwest wall also by pine forest. In the area around the crater, outcrops are confined mostly to fault scarps and stream channels and to places where trees blown down by wind reveal the rocks their roots penetrated.

The oldest rocks exposed within the crater walls are part of the upper ignimbrite unit of the Peyerl Tuff. The base of this ignimbrite is not exposed in the crater but is assumed to be about 4.5 m. below the lowermost outcrop in the west wall, 52 m. above the crater floor. Excavation to a depth of 3 m. showed decreasing welding and at a depth of 2.40 m. the basal pumice layer. Of the total thickness of 17 m. estimated for this locality, the lower 5.5 m. are densely welded, dark grey to brownish red and vertically jointed. Irregular horizontal platiness is due to welding. The upper, less densely welded part, 11.5 m. thick, is pink to grey and shows irregular widely spaced columnar jointing. The upper part is less resistant to erosion and weathers with rounded and cavernous surfaces. The upper part is slightly vesicular, but towards the contact with the overlying Paulina Basalt the ignimbrite shows evidence of baking. This contact is well exposed in the northwest and west side of the crater wall. Outside the crater, exposures of this ignimbrite are common along the northwest-trending fault, west of the crater, and to the south where it lies just beneath the surface. In the west, north and east walls the ignimbrite is overlain by Paulina

Basalt flow No. 2 which has an average thickness of 10 m. (max. 16 m., min. 5.5 m.) and is nearly continuously exposed at an elevation of 70 to 80 m. above the crater floor. The base of the flow is normally vesicular for about 0.3 m., the middle part dense and the upper 0.6-2 m. again vesicular. The largest vesicles are about 10 cm. long. Locally in the northwest and eastern walls, just north of a small fault, scoriaceous zones and small lava tubes can be observed. Columnar jointing is rather irregular, single columns being as much as 4 m. in diameter. Horizontal joints are also common in the uppermost part but less frequent in the middle. Delicate flow surface structures are not preserved, although there are a few pressure-ridges, mostly in the northeast wall. Horizontal or vertical vesicle zones can be found in the otherwise dense middle part of the flow. These are associated with zones of larger crystals.

Outside the crater this basalt flow occurs along the northeast- and northwest-trending faults, east and west of the crater, respectively. The basalt is not found south of the crater and is also missing immediately above the ignimbrite in the southwestern wall where the ignimbrite is overlain instead by fluviatile beds.

After deposition of the Paulina Basalt normal faults with displacements of up to 15 m. cut rocks in the near vicinity of Hole-in-the-Ground. One fault, 1 km. southwest of the crater trends northwest for about 4 km.; its uplifted side is to the northeast. The second fault occurs 1 km. southeast of the crater, trends northeast and is uplifted on the northwest side for about 5 km. Toward the southwest a third fault, 6 km. long, is en chelon with respect to the northeast-trending fault just mentioned.

A northwest-trending fault southeast of Hole-in-the-Ground can be traced for about 3 km. in a northwest direction into the northeast wall of the crater. The Paulina Basalt southeast of the crater as well as in the crater wall shows a displacement of about 10 m., the uplifted side being to the northeast. In the northern crater wall no fault displacement can be detected. Nevertheless the Paulina Basalt in the north wall seems to be tilted with its west side depressed about 7 m. lower. This suggests that the fault continues as a flexure. Since both northwest-trending faults are uplifted on the northeast, the crater was mainly formed in a block bounded by two step-faults, but the vent has no apparent relation to the pattern of intersecting faults. The crudely rectangular form of the crater is controlled by joints that strike northwest and southwest.

In several trenches dug by hand from the top of Paulina Basalt upwards into the basal layers of the eruption products fluviatile beds were found to form the uppermost horizon below the ejecta of the crater rim. These beds were also found in the west wall above the ignimbrite. The thickness of these sandy to fine-conglomeratic beds varies from 1.8 m. to over 6 m. The pebbles are rounded, subangular, and angular and have a maximum diameter of 5 cm.

These fluviatile beds were deposited shortly before the initial eruptions at Hole-in-the-Ground. They contain a small amount of pyroclastic material mixed with a variety of erosional detritus.

Bedding is poor, although in some sand-sized layers it is good, and even cross-bedding has been observed. Pebbles consist of the underlying Paulina Basalt flow No. 2, the upper ignimbrite including both densely welded and less densely welded types, gray fine-grained andesites and dark gray fine-grained basalt. Single feldspar crystals and few pumice fragments were also observed. The cementing material is yellow to brownish tuff. In the northern and southwestern walls there are a few interbedded greenish tuff layers higher in the section. Some of these layers contain pisolites. It was not possible to establish whether these beds represent initial eruption products of Hole-in-the-Ground or are derived from eruptions elsewhere.

Conglomerates were only found in the crater walls and are not seen to the east or west of the crater between the Paulina Basalt and ignimbrite. This distribution suggests that a stream may have flowed from the north, south or southeast and deposited the conglomerates in a flat stream bed. It is not known whether the front of the lava functioned as a cliff over which the stream cascaded. The remarkable thickness of the deposits indicates that there was abundant water in the area, at least when the conglomerate was deposited. It is therefore suggested that these fluviatile beds were deposited during a pluvial period and that stream water entered Fort Rock lake about 4 km. southeast of the crater. It is not yet known when the stream began to cross the area or with which level of Fort Rock lake it should be correlated. Judging from the amount of consolidation and the age of Hole-in-the-Ground (which will be discussed later) it is very tentatively suggested that these beds were deposited about 15,000 to 20,000 years ago.

The landscape at this time was rather flat, with a maximum relief of about 30 m. along a few faultscarps and stream valleys, such as the one that crossed the present site of the crater. After deposition of the fluviatile beds, Hole-in-the-Ground was formed and the eruption deposits formed a crater rim up to 80 m. above the surrounding plain. The products of this eruption are described below.

Sometime after the eruption of Hole-in-the-Ground, the third Paulina Basalt flowed down from the upper slopes of Newberry volcano, encountered the northern base of the crater rim, parted and flowed around the western and eastern sides over a large area of ejecta around the crater before dropping over the faultscarps and entering Fort Rock Basin.

On the flat floor of Hole-in-the-Ground several low arcuate ridges can be observed in the center and near the margins other concentric lines can be seen on aerial photographs. These are interpreted as terraces of a small shallow crater lake. A hole dug in the crater floor revealed dark brown heavy silt below the Mazama pumice. This silt, which also crops out in the center of the crater floor, is believed to be a lacustrine deposit.

The highest terrace (elevation about 1340 m.) is at the same level as Fort Rock Lake was prior to 13,000 years b.p. From this it is deduced that Hole-in-the-Ground was formed nearly at the same time as Fort Rock Lake reached the 1340 m. level, presumably 15,000-20,000 years ago. When the level of Fort Rock Lake subsided, the level of the crater lake also dropped leaving several younger terraces lower on the crater floor. It is certain that the crater floor prior to deposition of the lake beds was not as flat as it appears today.

About 7,000 years ago the whole area was evenly blanketed by Mazama pumice which in this area is about 60 to 70 cm. thick but gradually thickens to the west and thins eastward. Pumice from Newberry crater has not been identified.

Eruption Products

The eruption of Hole-in-the-Ground covered an area of 100 km². with a blanket of ejecta varying in thickness from about 80 m. on the east rim to a few millimeters 4 or 5 km. away. The overlying layer of Mazama pumice covers most of the pyroclastic material outside the crater, but there are exposures inside the crater, but mainly along horizons that are more resistant to erosion and contain numerous large blocks. These horizons are easily picked out on aerial photographs. They have been designated A, B, C, and D, A being the lowermost. Horizon A can be clearly traced on aerial photographs along much of the northeastern and northern walls but is difficult to see on the ground. Its elevation varies between 3 and 10 m. above the top of Paulina Basalt flow no. 2 and nearly coincides with the base of the pyroclastic deposits. Horizons B and C can be traced along the east and north wall, but most outcrops are confined to the NE and E wall. C is about 12 to 15 m. below the rim and B is 10 to 12 m. below C. Horizon D can be traced nearly continuously around the crater a few meters below the rim. It has the best exposures of all the eruption deposits. The thickness of the four horizons is about 2-4 m. Few outcrops have been found between the main horizons in the northeast and eastern wall and none are exposed below A. The base of the sequence was exposed in shallow trenches in order to study the lowermost layers.

The bulk of the eruption products consists of gray, green-gray or brownish gray consolidated tuff. The grainsize is dominantly below 4 mm. Few of the coarser layers or lenses with particle sizes of up to a few centimeters are more than 10 centimeters thick. Variations in grain size are also produced by accretion of fine-grained dust into pisolites of a size of up to one centimeter. These form layers several meters thick, but individual pisolites occur singly within the fine material.

To determine their grain-size distribution, consolidated tuffs were subjected to various disaggregation methods. The most effective separations were obtained in an ultrasonic cleaner. The resulting grain size distributions for two samples are shown in cumulative curves in figure 13. Since these two samples are believed to be representative of the bulk of the ejecta, it can be seen that about 90% of the tuff particles are smaller than 4 mm., and the median diameter is in the range of 0.2-0.7 mm. The regularity of this distribution may be a result of a milling process which Papenfuss (1963) and Weiskirchner (1967) propose to explain similar material in the tuff pipes of southern Germany. This would imply that the various rock types involved in the eruption were subjected to intense crushing prior to being erupted. The efficiency of this process seems to require long continued trituration rather than separate violent eruptions with intermittent periods of repose. The limited number of horizons that contain large blocks and the scarcity of bedding except in a few of the main horizons is consistent with this conclusion.

Embedded in these rather uniform deposits are blocks measuring up to several meters across. The largest one found was about 8 x 3, 5 x 2.5 m. Blocks in the range of centimeters or tens of centimeters are also common but there is a marked size gap between the very fine-grained tuff and the



Figure 11. Exposures of bedded tuff in horizon D, north wall.

blocks. Larger blocks with a diameter of more than 1 meter are definitely confined to the main horizons A, B, C, and D, as can be seen in fig.

Bedding does not occur throughout the sequence, but is confined mainly to the very base of the sequence and to the main horizons. The thickness of individual beds varies from a few centimeters and half a meter. Slight grain-size differences and different proportions of juvenile material, pisolites or ejected blocks distinguish individual beds. Grading has been seen but is uncommon, and cross bedding is absent. Within horizons B, C, and D, bedding planes are often very irregular in orientation; locally they may be nearly vertical where large blocks fell on the surface. In horizon A these features could not be found because few outcrops have any sign of bedding. The attitude of the ejecta is horizontal or dipping slightly outward from the crater at angles up to about 10° . Inward dipping beds were not found.

Outside the rim exposures found in the roots of fallen trees usually are well bedded with individual beds measuring 5 to 20 centimeters thick. Between the main horizons bedding seems to be nearly absent and the tuffs are uniform and fine-grained. There are a few blocks but both measure less than tens of centimeters. It is impossible to correlate layers outside the crater with those in the crater walls.

The basal tuff layers do not differ materially from the rest of the rest of the deposit. They contain angular blocks up to 10-15 cm. in size and include all the rock types found higher in the section. Crude bedding is locally developed. About 1 m. above the base there are unbedded blocks 20 to 40 cm. in diameter. These basal layers which are now exposed about 620 m. from the center of the crater presumably do not represent the very first eruption products. Since they are bedded and do not contain large blocks, it is deduced that the eruption did not

begin suddenly or violently. The first products were probably deposited closer to the initial vent and were removed and redeposited by subsequent eruptions.

Ejected Blocks

The fragmental rocks that rim Hole-in-the-Ground provide the best information on the nature of the explosive eruptions responsible for the crater. For this reason they deserve special attention. The most conspicuous ejecta are the large blocks scattered about the rim. Within the sequence of ejecta, these blocks are confined mainly to the resistant horizons A through D (fig. 12, 15). Smaller blocks are to be seen between the main horizons, and blocks are also scattered outside the rim on the surface of the tuff deposits, partly covered by Crater Lake pumice.

Measurements of the largest dimension of blocks in horizons B, C, and D revealed the following size distributions:

Table 1. Number of Blocks of Different Sizes in Horizons B, C, and D.

Horizon	Maximum Diameter in Meters							total
	2	3	4	5	6	7	8	
D	25	24	7	2	-	-	1	59
C	3	6	5	3	-	-	-	17
B	4	5	1	-	-	-	-	10
Total	32	35	13	5	-	-	1	86

A good statistical evaluation is not possible because of the limited number and size-range of blocks that were tabulated and the possibility

- Mazama Pumice
- === Bedding
- Fine grained tuff
- ○ ○ Round or angular blocks
- ==== Fluvatile beds
- ||||| Paulina Basalt Flow No. 2

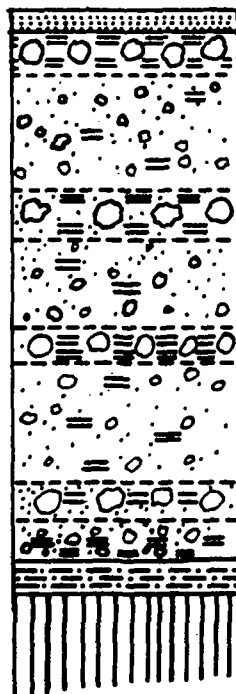


Figure 12. Schematic stratigraphic section through the eruption products of Hole-in-the-Ground.

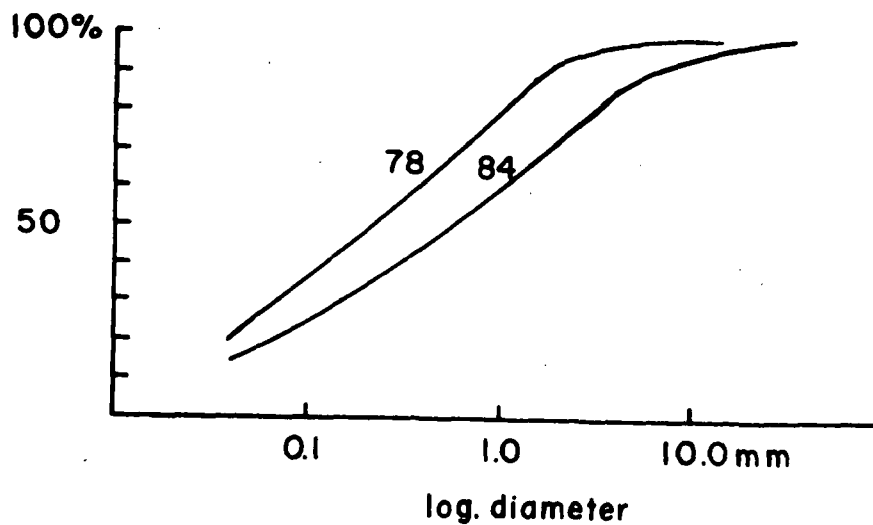


Figure 13. Grain-size distribution in two typical samples of tuff.



Figure 15. A portion of the north wall of the crater including horizons C and D.



Figure 16. Largest block of horizon D exposed in the east wall. Hammer indicates scale.

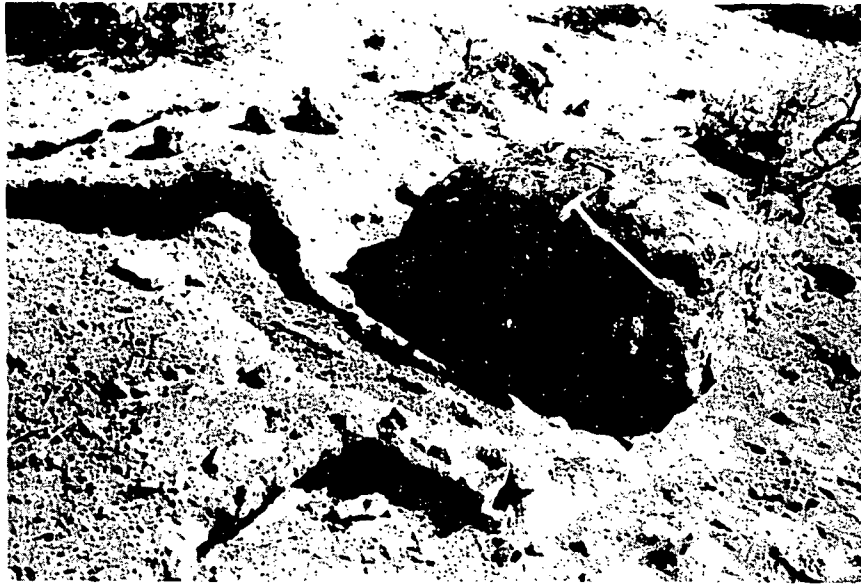


Figure 17. Rounded block with impact sag, north wall, horizon D.



Figure 18. Angular block with impact sag, north wall, horizon D.

of subjective selections. It is apparent, nevertheless, that blocks of similar size were violently ejected with the materials of beds B, C, and D during the main eruptive episodes. This illustrates the difference between the main horizons and the bulk of the eruption deposits (fig. 21).

In the basal layers and in bed A, the fragments are mostly angular or subangular, whereas a remarkable amount of later ejecta in beds B, C, and D are subrounded or rounded (fig. 17, 19). Depending on the rocktype, some blocks are well-rounded while others are only partly rounded and partly polyhedral. Many of the angular faces of hard rocks are concave and had quite sharp edges when first erupted, then became subrounded with blunted edges with later eruptions. A few large fragments show several successive shells. This seems to indicate spalling, possibly due to thermal stresses. In other fragments, however, angular pieces of different size were broken off mechanically. The relative effects of the two processes must have depended on grain-size, texture and hardness of individual fragments. To a large degree, the shapes of blocks must also have been influenced by primary features, e.g. the irregular jointing of the Paulina Basalt. Many blocks preserve forms inherited from columnar structures, indeed blocks with a diameter above 3 m. always show relic columnar jointing.

Grooved Blocks

The surface of many blocks are smooth and polished while others have faces marked by parallel striations or grooves up to 2 cm. deep (fig. 19, 20). Most of these grooves occur on only one side of a block. On some blocks the grooves on adjacent faces have different orientations that have no relation to the original texture of the rock. Hence, the grooving cannot be a result of weathering. Some rocks in the



Figure 19. Grooved block in horizon D, north wall.



Figure 20. Close-up of grooved block of figure 19.

crater wall that still retain their original position and orientation have grooves only on the side facing the crater, there being none on the lower or rear sides. One 4 m.-block on the west rim, which broke into two pieces after impact, displays grooves on the fracture planes. As to the origin of the grooves, two possibilities arise: either abrasion by base surges or by wind erosion. Indications of base surges are rare at Hole-in-the-Ground. The best developed grooves are found on the northwest and north rims, precisely where Mazama pumice has been largely stripped by wind. Moreover, similar grooves have been found outside the crater, e.g. at the upper edge of the lava cap on Flat Top. The grooves are therefore interpreted as features of wind erosion, produced by abrasion by the glassy shards of Mazama pumice.

Most of the large blocks that still lie in situ in beds B, C, and D on the crater walls depressed the underlying layers (fig. 17, 18). The depths of some of these 'impact pits' and the diameters of the blocks that produced them are listed in table 2.

Table 2. Depth of Depressions Produced
by Blocks of Various Sizes

Block Dimensions in Centimeters

Horizon	Horizontal		Vertical	Depth of Impact Sag
D	12	12	7	5
D	30	20	12	6
D	30	24	15	10
D	25	25	16	15
D	20	20	20	25
D	60	40	35	35
D	40	40	40	40
D	80	80	45	40
D	60	50	50	30

<u>Horizon</u>	<u>Horizontal</u>	<u>Vertical</u>	<u>Depth of Impact Sag</u>
D	100	90	70
D	200	180	150
D	150	100	200
D	9	9	6
			10

As can be seen from table 2 the depth of the small impact sags exceed half the vertical dimension of the blocks, indicating the high velocity with which these blocks landed from flight.

Muzzle Velocities

To estimate ejection (muzzle) velocities, fragments outside the crater rim were mapped according to size-distribution. The results are shown in an isopleth map of the ejecta (fig. 22). On the upper and middle slope ejecta can be assigned to horizon D but where the thickness of the deposits is less than 3 meters the horizon to which the blocks belong cannot be determined.

Many blocks were found south of the crater but few to the west and east and almost none to the north. This reduces the reliability of the data. Nevertheless, the distribution of blocks indicates a slightly larger horizontal component momentum for those thrown to the southeast than for those blown in other directions. This indicates that the eruptions were not vertical. Wind certainly had little effect on the distribution of large blocks.

A plot of the maximum diameter of the ejecta against their distance from the crater (fig. 23) shows that the 3 m. isosize is too close to the crater and is therefore the least accurate of the contours. Few blocks were found on the upper slope and erosion has not yet cut through the surface blanket of Crater Lake pumice.

The equation for calculating ejection (muzzle) velocities is

$$V_0 = \sqrt{\frac{D \cdot g}{\sin 2\alpha}}$$

where D is the distance from the crater-center, g the acceleration due to gravity, and α the ejection angle. It indicates that blocks blown from the crater with an ejection angle of 45° travel farthest, other factors being equal. Therefore, at $\alpha = 45^\circ$

$$V_0 = \sqrt{D \cdot g}$$

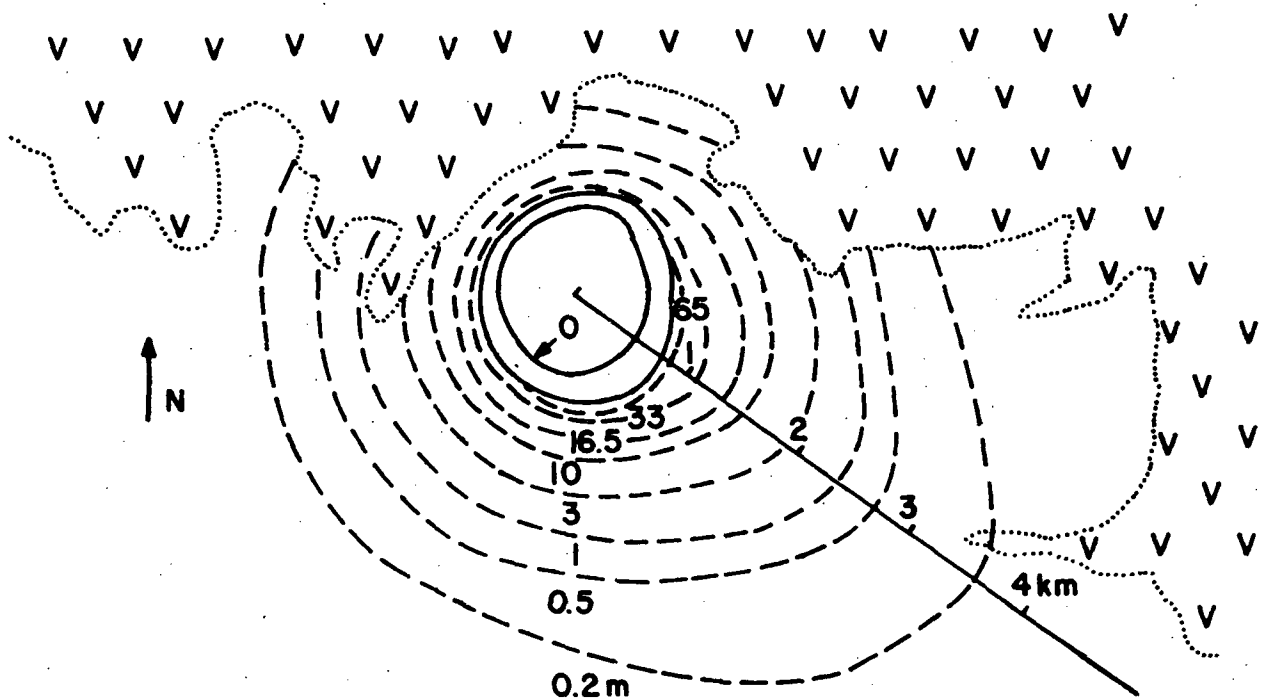
Since, at Hole-in-the-Ground, the eruptions that threw out large blocks were inclined toward the southeast, it is reasonable to assume that isopleths in that direction were reached by blocks of a given size ejected at 45° . Blocks thrown as far as 3700 m. to the southeast must therefore have had muzzle velocities of at least 191 m./sec. Taking into account air resistance and a form factor which changes the ideal parabolic flight path into a ballistic path where D is shorter and the impact angle steeper than the ejection angle, the true minimum initial velocity for those blocks was well over 200 m./sec.

Vertical heights of ejection can be calculated using the relation

$$H = \frac{V_0^2 \sin^2 \alpha}{2g}$$

For blocks of similar size that rose vertically from the vent ($\alpha = 90^\circ$) with $V_0 = 200$ m./sec., H is about 2 km. Owing to the thermal effect of hot, expanding water vapor an additional vertical component was added to this initial ejection velocity and the eruption cloud must therefore have reached even greater heights, perhaps 5 km.

The initial velocities of larger blocks which were not thrown as far as smaller blocks are given in fig. 24 assuming for their respective



V V V Paulina Basalt flow, No. 3

- - - Isopach, 1m

Figure 25. Isopach map of ejecta from Hole-in-the-Ground.

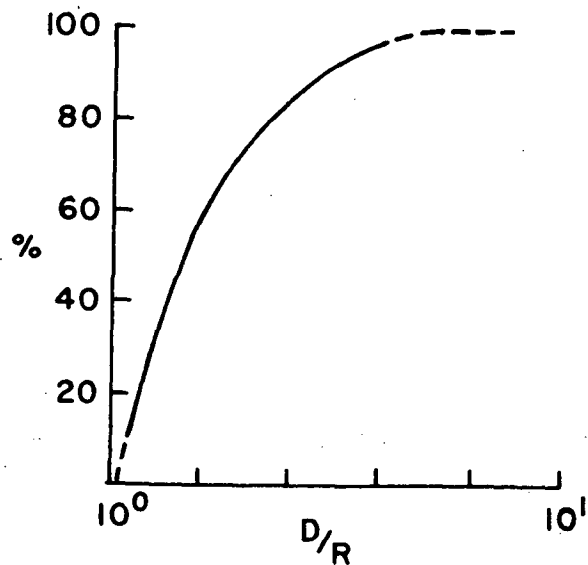


Figure 26. Mass distribution against crater radius for ejecta of Hole-in-the-Ground.

isopleths an angle $\alpha_{ab} = 45^\circ$. The resulting curve also indicates that the 3 m. isopleth is not correct and should be farther from the crater.

If we assume the source was a point and that the initial velocity of blocks thrown in all directions was the same as for the southeast their ejection angle can be determined. Owing to the qualitative limits of the isopleth map only the distances towards the southwest can be used with confidence. The ejection angles for blocks with a diameter of 2 m., 1 m., 0.5 m., and 0.1 m. are 66.2° , 68.9° , 65.5° , and 68.95° respectively. The maximum variation of 3.45° is negligible especially since there is no actual point source and exposures are not numerous.

The approximate inclination of the eruptions can be constructed from an equal angle projection and indicates that the axis of eruptions that threw out large blocks was inclined about 20° to 30° toward southeast. Blocks thrown toward the southeast and southwest deviated from the axis of eruption with maximum angles of 25° to 35° . The ejection cone given by the initial block ejection paths had a solid angle of about 50° to 70° . A vertical eruption at Hole-in-the-Ground would not have produced ejection angles of 45° but of at least 55° to 65° above the horizontal.

No blocks outside the crater rim can be assigned to pulses between the deposition of the major horizons. Therefore, no maximum velocities can be calculated for this material. Nevertheless blocks inside the rim-crest at the base of the ejecta blanket or between the major horizons A, B, C, and D are 600 to 800 m. away from the eruption center. Thus their initial velocities must have been at least 80 to 90 m. per sec., even for blocks at the base of the deposits. If air resistance, form factor

and size are taken into account, maximum velocities of more than 100 m./sec. were certainly reached by some blocks.

Apparent Fluid Velocity and Density at the Orifice

Calculation of the inertia, $m \cdot V_o$, of blocks of various sizes indicates that the momentum of large blocks was about 5 orders of magnitude larger than that of small blocks. Since there was little size sorting of the blocks, it is apparent that the eruption mechanism did not impart to the different blocks a uniform momentum.

A possible explanation of the relative velocities may be found in the effect of a dense gas-particle system of high velocity. As a first approximation, an equilibrium situation may be assumed in which the initial velocities of large and small blocks are related to a uniform fluid density and a single apparent fluid velocity of the rising gas-particle system. Actually, such a condition would not be possible near the surface where the high pressure gradient causes the gas volume and velocity to increase rapidly as the density and viscosity decrease. Because of their greater inertia, large blocks will not react to these changes as fast as small ones, but very little difference is observed between blocks of different sizes. Another simplification requires that the blocks be free from mutual interference and that the flow pattern around large blocks be similar to that around small blocks, i.e. that the ratios of Reynolds number to Froude number are assumed to be nearly the same for all blocks of the selected size range.

Blocks leaving the crater have an initial velocity of V_o which differs for different block diameters (fig.24). The velocity of the fluid responsible for drifting the blocks is V_f and is related to V_o

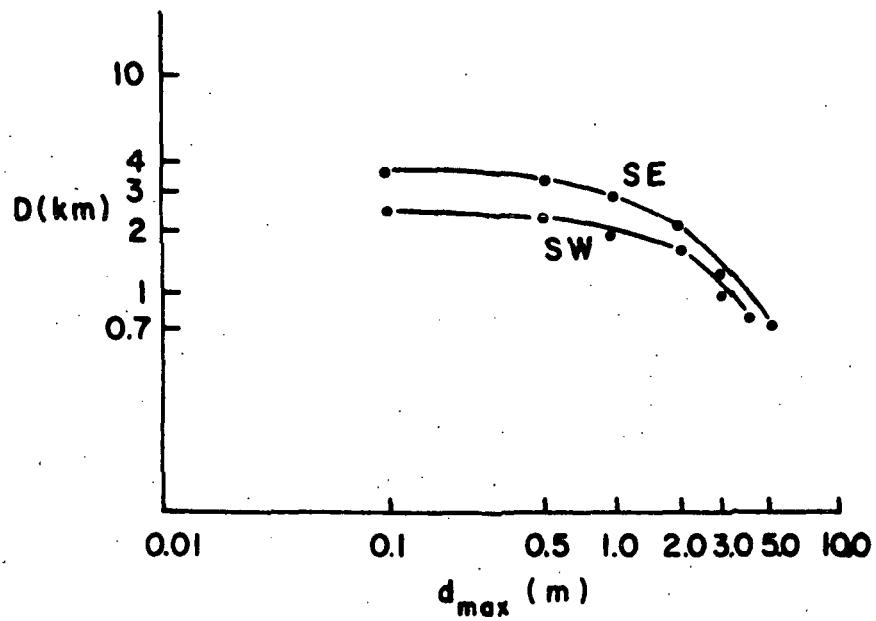


Figure 23. Relationship between maximum block diameters and maximum ejection distances from the center of the crater.

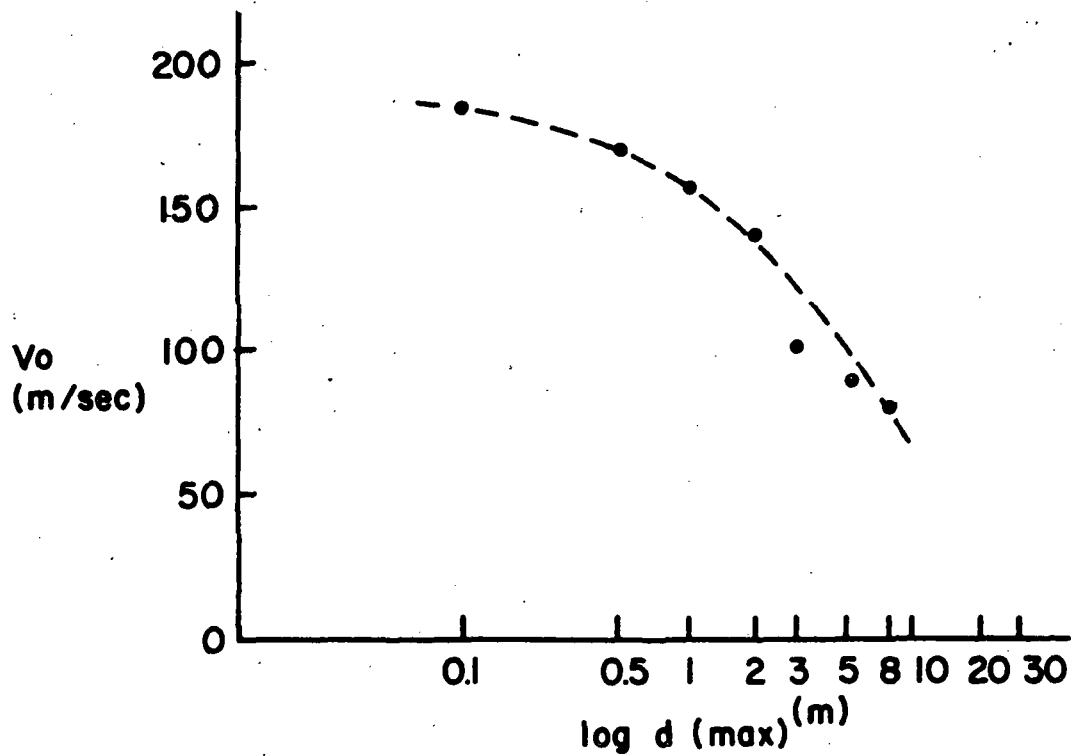


Figure 24. Relationship between maximum block diameters and initial ejection velocities.

by the equation:

$$V_t = V_f - V_o.$$

V_t is the velocity of the fluid needed to support the blocks; this is also the terminal velocity the blocks would reach when sinking through the same fluid. Both V_t and V_o are related to the block diameter.

V_o is known for the different block sizes, but V_f and V_t are unknown.

For spherical blocks, the terminal velocity is:

$$V_t = \sqrt{\frac{8 \cdot g \cdot \gamma (e_s - e_p)}{3 \cdot C \cdot e_p}}$$

where e_s is the density of the block, e_p the density of the fluid, and C is the drag coefficient in turbulent flow. If a typical value of C is taken as 0.4 a constant of:

$$\sqrt{\frac{8}{3} \cdot \frac{g}{C}} = 81$$

is derived. For irregular fragments of quartz where the drag coefficient is larger, experiments in air have shown the constant to be 71 (Hardinge and Frankish, 1945). Applying this constant the equation becomes:

$$V_t = 71 \sqrt{\frac{e_s - e_p}{e_p} \cdot \gamma}$$

Both V_t and e_p are unknown in this equation; e_s is taken as 2.7 g./cm³.

By varying e_p for the different block diameters, values of V_t can be calculated. The only set of V_t values that will be useful is the one which can be added to the respective V_o values to give only a constant value for V_f :

$$V_f = V_{t_1} + V_{o_1} = V_{t_2} + V_{o_2} = V_{t_3} + V_{o_3}$$

As can be seen in table 3, at a density of 0.04 g./cm³, the fluid velocity V_f is nearly the same for the different block sizes, i.e. about 198 m./sec.

Table 3 : Values of fluid velocities and fluid densities for variable
block diameters.

V_o m/sec	d cm	r cm	V_t (m/sec) at $\rho_f : 0.02\text{g/cm}^3$	V_f m/sec	V_t (m/sec) at $\rho_f : 0.03\text{g/cm}^3$	V_f m/sec	V_t (m/sec) at $\rho_f : 0.04\text{g/cm}^3$	V_f m/sec	V_t (m/sec) at $\rho_f : 0.05\text{g/cm}^3$	V_f m/sec	V_t (m/sec) at $\rho_f : 0.06\text{g/cm}^3$	V_f m/sec
140.5	200	100	82.2	222.7	67.0	207.5	58.0	198.5	51.7	191.7	47.2	187.2
157.0	100	50	58.2	215.2	47.5	204.5	41.0	198.0	36.6	193.6	33.2	190.2
172.0	50	25	41.0	213.0	33.6	205.6	29.0	201.0	25.8	197.8	23.6	195.6
186.0	10	5	18.3	204.3	14.9	200.9	12.9	198.9	11.5	197.5	10.5	196.5
191.0	2	1	8.2	199.2	6.7	197.7	5.8	196.8	5.2	196.2	4.7	195.7

Within the limits of the assumptions made above, a fluid system with a density of 0.04 g./cm^3 and a velocity of 198 m./sec. could produce the different initial ejection velocities of blocks of various sizes carried by the fluid. Since the final pressure drop near the surface causes a rapid increase in gas volume and velocity and a rapid decrease in density, the calculated fluid velocity and density would be reached only near the end of the pressure drop. The true velocity must have been somewhat higher and the density lower than the calculated values since equilibrium cannot be assumed to have been established immediately. When account is also taken of frictional losses and the fact that the calculation was based on a parabolic rather than a ballistic trajectory, the fluid velocity of the strongest eruptions at the crater was probably close to 220 to 240 m./sec.

The largest blocks ejected between deposition of the main horizons have diameters of approximately 1 m., and because they are found from 600 to 800 m. away from the center of the crater, they were ejected with initial velocities of at least 80 to 90 m./sec. If we assume that the eruption clouds during the intermediate eruptions had about the same fluid density as those during the major eruptions, the fluid velocity can be calculated using the blocks of 1 m. diameter. Their terminal velocity in a fluid of 0.04 g./cm^3 is 41 m./sec. (table 3). If their initial velocity was 90 m./sec., the fluid velocity was about 130 m./sec. The maximum distance to which blocks 10 cm. in diameter, ejected at 45° , were hurled was 1400 m. and their initial velocity was 118 m./sec. Assumption of greater fluid densities for the intermediate eruption clouds would lead to smaller fluid velocities; assumption of lower fluid density would lead to larger fluid velocities.

The largest block thrown out of the crater during the major eruptions has a maximum diameter of 8 m. and is found 700 m. away from the crater center. The diameter of blocks that were just supported in the rising fluid at the crater can also be calculated as their terminal velocity is the velocity of the fluid:

$$V_t = V_f = 198 \text{ m./sec.}$$

Hence the radius of blocks that are just supported is 11.7 m., and their diameter is about 23 m. It is not certain, however, that such blocks were available since all the rocks are strongly jointed. If even larger blocks were available near the surface they must have subsided within the fluid until their size decreased enough to allow them to be supported and drifted upward by the rising fluid. The equilibrium size for blocks of the intermediate eruptions was about 10 m.

The effect of the depth of the vent on the fluidized system is not known. It is clear, however, that the equilibrium size in the depth range where blocks became rounded before being ejected during the major eruptions was larger than 3 m. Blocks larger than 3 m. are angular and must have been part of the fixed bed during the intermediate eruptions, blocks smaller than 3 m. show rounding and were probably part of the fluidized system.

Particle Concentration in the Eruption Cloud at the Orifice

The fluid consisted of water vapor carrying small particles with a density of about 2.7 g./cm^3 and a median diameter of about 0.5 mm. (fig. 13). If the water vapor is assumed to have been saturated, at a pressure of about 1 bar and a temperature of 100°C. , it had a density of 0.000598 g./cm^3 . One cm^3 of fluid with a density of 0.04 g./cm^3 then

contains about 0.0395 g. of solid material which is equivalent to 39 kg./m^3 . or 224 round particles of a diameter of 0.5 mm. in one cm^3 .

If the water vapor is taken at a pressure of 10 bars and a temperature of 180°C ., its density is 0.00516 g./cm^3 . One cm^3 . of fluid then contains 0.035 g. of solid material, which is equivalent to 35 kg./m^3 . or 198 round particles of a diameter of 0.5 mm. in one cm^3 .

To check the usefulness of this approximation a simple comparison can be made. A cylindrical eruption cloud 2000 m. high, 100 m. in radius, and with a particle concentration of 39 kg./m^3 . contains $2.45 \cdot 10^9 \text{ kg.}$ of solid material. On the other hand an ejecta blanket 10 km^3 . in area, 10 cm. thick and of an average density of 2 g./cm^3 . contains $2 \cdot 10^9 \text{ kg.}$ The deposition of such an ejecta blanket from an eruption cloud of the above size is reasonable and indicates that the calculated value for the fluid density cannot be greatly in error.

From the particle concentration $c_g = 0.0395 \text{ g./cm}^3$, we can calculate the voidage ϵ .

$$c_g = (1 - \epsilon) e_g$$

$$(1 - \epsilon) \cdot 2.7 = 0.0395$$

$$\epsilon = 0.9854$$

The fluid at the crater therefore consists of 98.5 volume percent gas and only 1.5 percent solids.

Eruption Pressures

Using Bernoulli's theorem the velocity producing pressure can be estimated for the crater opening:

$$P_1 + \frac{1}{2} \rho \cdot V_1^2 + \rho \cdot g \cdot h_1 = P_2 + \frac{1}{2} \rho \cdot V_2^2 + \rho \cdot g \cdot h_2$$

where P_1 is the pressure just before the eruption and P_2 is the pressure of the surrounding area; ρ the density, V_1 and V_2 velocities before and after the eruption, g the acceleration due to gravity and h_1 and h_2 different heights. ρ is taken as 2.7 g./cm^3 . for the basaltic ejecta, P_2 is 0.981 bar or about 0, V_1 is also 0 and V_2 is taken as 200 m./sec.; h_1 and h_2 at the crater opening are equal. Thus the equation is reduced to $P_1 = \frac{1}{2} \rho V_2^2$ and the eruption pressure (orifice pressure) is found to be 540 bars.

If an eruption started at a depth of 500 m., $p \cdot g (h_2 - h_1)$ has to be considered which is $2.7 \times .981 \times 10^2 \times 0.5 \times 10^5 = 132$ bars. Hence the pressure just prior to the eruption was about 0.67 kbar at the eruption focus. Since part of the energy was lost in brecciation of rocks, turbulence and friction, the original pressure at the eruption source, assuming a depth of 500 m., would have been of the order of 700 bars.

Since only smaller blocks were ejected between deposition of the main horizons, the intervening eruptions were less violent and initial ejection velocities were correspondingly much smaller, perhaps of the order of 130 m./sec. as given above. Pressures at the orifice were then about 228 bars and the pressures at the eruption foci about 400 bars.

These results indicate that at least four times during formation of Hole-in-the-Ground, extremely high pressures were effective in the ejection of large blocks. A schematic diagram showing variations of eruptive energy with time is given in fig.21.

Petrographic Notes on Ejecta-Types

In order to determine the depths of the explosion foci, various kinds of lithic fragments were examined and an attempt was made to assign them to their proper stratigraphic positions. Thirteen rock-types were recognized. The following notes concern their petrographic characters, relative abundance, and sizes.

1. Paulina Basalt Flow No. 2. The largest block measures 2.5 m. across.
2. Upper and lower ignimbrites of Peyerl Tuff unit. The largest block measures 3 m. across. Most blocks that can be identified as members of this unit came from the lower, densely welded part of the two ignimbrites. Blocks derived from the upper parts are less common because they are less resistant. All blocks tend to be tabular.
3. Porphyritic basalt. The most abundant and most conspicuous blocks are of porphyritic basalt with feldspar crystals that reach a length of 1.5 cm. Some of these blocks are markedly vesicular; the largest block measures approximately 5 m. across.

In thin section, about a third of the basalt is seen to be made up of zoned phenocrysts of sodic labradorite, up to 5 mm. in length. Between a fifth and a third of the pilotaxitic groundmass consists of sub-parallel microliths of plagioclase that range in composition from sodic labradorite to calcic andesine. Clinopyroxene ($2V_2 = 48^\circ$), in part ophitic, makes up an equal volume, while olivine, partly altered to iddingsite, makes up between 3 and 8 percent. The content of opaque oxides varies from 5 to 20 percent.

4. Light gray porphyritic olivine basalt. An uncommon but easily recognized type is a basalt that contains large phenocrysts of both plagioclase and olivine. It is readily distinguished from type 3 because its plagioclase phenocrysts are only about half as abundant. The largest block measures 8 m. across.

In thin section, the plagioclase phenocrysts, most of which measure from 2 to 4 mm. in length, show normal and reverse zoning within the compositional range of sodic labradorite. They make up roughly 15 percent of the total volume, whereas the laths of calcic andesine in the groundmass make up about 35 percent. Clinopyroxene ($2V_2 = 48^\circ - 51^\circ$), in grains up to 1 mm. in maximum dimensions, makes up 37 percent of the whole. Olivine, though not abundant (3 - 4%), forms phenocrysts between approximately 1 and 2.5 mm. in maximum dimensions. Iron ore (ca. 7%) and glass (1.5 - 3.0%) constitute the remainder. As will be described later both types, 3 and 4, are found as lavas within the vent wall at rather shallow depth and may be considered part of the Hayes Butte Basalt.

5. Fine-grained, light-to medium-gray basalt. This type is very common and conspicuous. Many blocks have roundish forms with concave faces; none are vesicular. The largest block measures 4.5 m. across.

Thin sections reveal a few microphenocrysts of zoned sodic labradorite with a maximum length of approximately 1 mm. These, together with sub-parallel microliths of calcic andesine in the groundmass, make up between 40 and 50 percent of the bulk. Small grains of clinopyroxene ($2V_2 = 52^\circ - 53^\circ$), few of which exceed 0.1 mm. in greatest dimension, constitute between 28 and 37 percent by volume. Partly altered crystals

of olivine, between 0.06 and 1.3 mm. long and about half as wide, account for 3.5 to 8 percent. The content of iron ore ranges from approximately 10 to 20 percent. Glass may be absent, and at most makes up less than 2 percent of the volume. The texture of the andesite is intergranular and fluidal.

The source of this type of rock is not known but must be at a depth greater than that of type 3.

6. Dark gray, partly vesicular basalts. Only a few blocks of this type were found. Two varieties are distinguishable in thin sections. One is almost devoid of plagioclase phenocrysts, its clinopyroxene (25%) is not ophitic, and olivine accounts for about 4 percent of the volume. The other variety contains more plagioclase phenocrysts and fewer olivines (21%), and its clinopyroxene (43%) is partly ophitic. The source of type 6 is not known.

7. Welded ignimbrite. Black, dense glassy blocks, usually between 5 and 15 cm. across, with a maximum observed diameter of 60 cm. Many blocks of this type are somewhat rounded and have one or more polygonal, concave faces. Their originally sharp edges have been smoothed by abrasion.

In thin section, the ignimbrite is seen to consist of glass shards and larger glass fragments ($n = 1.496 - 1.500$) that are firmly annealed and exhibit a marked fluidal texture. A few crystals of plagioclase and clinopyroxene are present, mostly less than 0.7 mm. in maximum dimension. There are also lithic fragments of acid to basic volcanic rocks.

Blocks of this type were undoubtedly derived from the basal welded part of an ignimbrite sheet. The upper ignimbrite of the Peyerl Tuff has

no such glassy base and its glass has a refractive index of 1.528. The base of the intermediate ignimbrite is not exposed, but the refractive index of the glass (1.516) in the exposed part is distinctly higher than that of the ejected blocks. Black glass found in a core from the lowest ignimbrite penetrated in drillhole No. 1 (table 5) has the same refractive index (1.496 - 1.500). This suggests that the blocks of black welded ignimbrite were derived from the lower ignimbrite sheet of the Peyerl Tuff, i.e. from a depth of approximately 135 m. below the surface.

8 and 9. Intermediate to felsic rocks. These are the least common types of blocks. Most of them measure 10 to 20 cm. in diameter, and even the largest is only 0.5 m. across. Two types are easy to recognize.

In thin section, type 8 is seen to contain tabular phenocrysts of zoned andesine with inclusions of apatite. These phenocrysts range from 1.5 to 3 mm. in length and 0.5 to 1.3 mm. in width, and make up 14 to 25 percent of the total volume; sub-parallel microliths of plagioclase in the groundmass make up 40 to 60 percent. Phenocrysts of pale green clinopyroxene ($2V_2 = 51^\circ - 52^\circ$), up to 1.4 mm. in greatest dimension, comprise 2.5 to 7 percent, while groundmass clinopyroxene comprises less than 5 percent. Granules of ore, on the other hand, comprise between 20 and 25 percent of the whole. Interstitial brown glass is present but only in trace-amounts. The texture of this type of block is porphyritic, intergranular, and in hand specimens the blocks have violet to brown colors, with reddish brown crusts.

Type 9, a dacite, also contains tabular phenocrysts of plagioclase (14 - 25%), with apatite inclusions, and abundant plagioclase microliths

in the groundmass. And, in addition to microphenocrysts of clinopyroxene, it carries poikilitic crystals of quartz that measure 0.6 mm. across.

Ore and glass are accessory constituents. The rather coarse grain of the groundmass suggests that this rock-type may be of intrusive origin.

The sources of these intermediate to felsic rocks are unknown.

Fragments of similar composition and texture are present as inclusions in ignimbrites of the Peyerl Tuff unit, that may have been a source of some blocks. It is also possible that the blocks were not derived from lavas or intrusive rocks in the walls of the conduit underlying Hole-in-the-Ground, but from bouldery interbeds.

10. Intermediate ignimbrite. Only a single piece of this rock was recognized. It measures approximately 50 cm. in diameter. Its bluish gray matrix contains gray- to brown-colored fragments of pumice, waterworn pebbles, and small chips of obsidian. Thin sections reveal very distinctive brown glass shards and pumice fragments with the same refractive index ($n = 1.512 - 1.516$) as that of the glass shards in the intermediate ignimbrite.

11. Dark to black pumice. Two pieces of this type were found, each containing a few phenocrysts of plagioclase, clinopyroxene, and olivine. Similar pumice is present within the Peyerl Tuff unit between the two ignimbrites.

12. White to yellowish pumice. A few minute fragments are present among the ejecta; presumably they were derived from pumiceous layers within the Peyerl Tuff unit.

13. Volcanic pebbles. Pebbles of various volcanic rocks, mostly 0.5 to 5 cm. across, are also present. They may have been derived from

fluviatile beds that overlie Paulina Basalt Flow No. 2 or from other fluviatile beds farther down in the sequence.

To summarize, only the origins of ejecta of types 1, 2, 10, and 11 are well-established from field-data, of types 3 and 4 also from drill-hole data. Types 3 and 4 are closely related and may be considered members of the Hayes Butte Basalt. Types 7, 12, and 13 were presumably derived from the Peyerl Tuff unit and the same may apply to types 8 and 9. The source of types 5 and 6 are unknown.

Present evidence therefore indicates that the conduit underlying Hole-in-the-Ground extends downward at least as far as the middle or basal parts of the Hayes Butte Basalt. There is no evidence thus far that the conduit extends down to the Picture Rock Basalt, though it may be that this is absent beneath the crater.

Frequency Distribution of Ejecta

At four different places, D-horizon - west wall, D-horizon - east wall, C-horizon - north wall, B-horizon - northeast wall, the frequency distribution of six main rock types found as ejecta was studied by examining about 100 large blocks at each site (table 4). Other rock-types amount to less than 1% and were not counted.

Despite the small variations, the frequency distribution reveals a remarkable similarity between the different horizons. This suggests that explosive discharge of wall rocks did not change materially during the eruption, at least between the deposition of beds B and D. No new rock types appear in horizons C and D that are not present in B. It appears unlikely, therefore, that the eruption-foci shifted in time

Table 4 : Frequency distribution of six main rock types found as ejecta
(in numbers of blocks counted, %)

Location	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Sum
D, W-wall	5.9	4.9	50.0	7.85	23.5	7.85	100.0
D, E-wall	10.5	3.85	43.2	15.5	20.2	6.75	100.0
C, NE-wall	9.4	4.7	45.2	9.5	28.3	2.9	100.0
B, NE-E-wall	16.0	8.5	46.2	7.55	19.8	1.95	100.0
Averages	10.45	5.49	46.15	10.1	22.95	4.86	100.0

vertically within the range of the lavas or ignimbrites. The relative frequencies do not throw any light on the shape of the vent since increase in width of a cylindrical vent or an inverted cone-shaped vent (with the solid angle increasing with time) will not be reflected in frequency changes. Only when an increase of diameter takes place within a restricted vertical interval of the conduit will the relative amounts of the block types be affected.

The basal layers and horizon A also contain all the main rock types found as ejecta in B, C, and D. Hence, we conclude that the levels at which eruptions were initiated were confined to certain depths from the very beginning and remained fixed throughout the eruptive episode.

Shape and Depth of the Conduit as Inferred from Ejected Blocks

The width of the funnel and crater increased continuously throughout the eruptions and expansion was probably most rapid during deposition of the main horizons. The final shape of the crater was certainly affected by slumping, as shown by the fact that no inward-dipping tuff-layers are preserved even though these must have been deposited (Shoemaker, 1957).

The ejecta of Hole-in-the-Ground crater may be considered a sample of the rock sequence penetrated by the pipe. Types 3, 4, and 5 together represent nearly 80% of the different ejecta types whereas Paulina Basalt Flow No. 2 and the upper ignimbrite represent only about 16%. This suggests that the most common hard rocks penetrated by the pipe are types 3, 4, and 5. If the pipe were cylindrical, the thickness of any stratigraphic unit would be directly proportional to its volume among the ejecta. The thicknesses of Paulina Basalt No. 2, and the lower part of the ignimbrite, which together contribute most of the ejecta, are known

to be about 10 and 7 m., respectively. Their corresponding frequencies among the ejecta are 10.5 and 5.5 percent. If the cross-section of the pipe is assumed to be half as large as it is at the elevation of Paulina Basalt No. 2 the following values can be derived for the thickness of the other ejecta types:

type 3: 92 m.; type 4: 20 m.; type 5: 45 m.; type 6: 9 m. Total 166 m.

The rocks penetrated by the pipe include resistant lavas and ignimbrites as well as much softer rocks such as fluviatile beds and tuffs. Logs of drill holes in the Fort Rock Basin show an average ratio of 1:3.4 (22.5% - 77.5%) for hard to soft rocks. Taking this ratio into account the total section penetrated by the pipe below the crater floor could be about 740 m., but in view of the many uncertainties on which this estimate depends it should be considered only a rough approximation.

Distribution of Ejecta

From known thicknesses, within the crater wall, and a few exposures on the lower outer slopes and from values inferred from topography, an isopach map of the ejecta has been compiled (fig. 25). Base level of the deposits within the crater wall was taken at an elevation of 82.0 m. above the crater floor.

The isopachs, like the isopleths of the ejecta (fig. 22), extend farther to the southeast than they do in any other direction. Deviation from circular lines is nearly the same as it is for the isosizes, proving that no appreciable wind prevailed during the eruptions in the lower atmosphere contrary to the view of Peterson and Groh (1961) who assumed

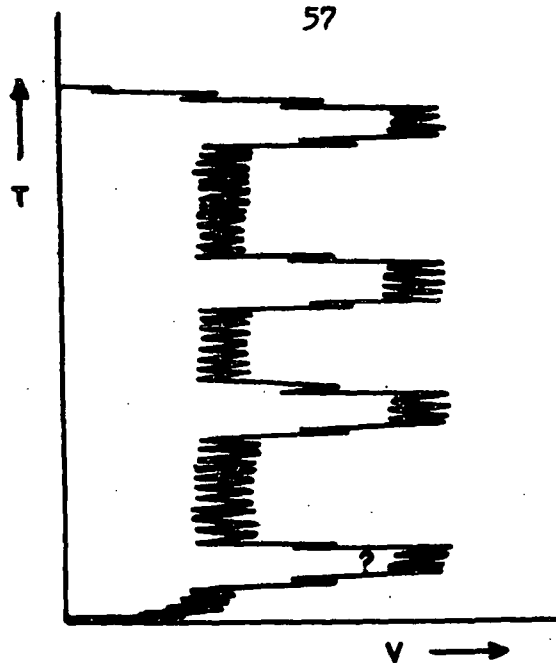
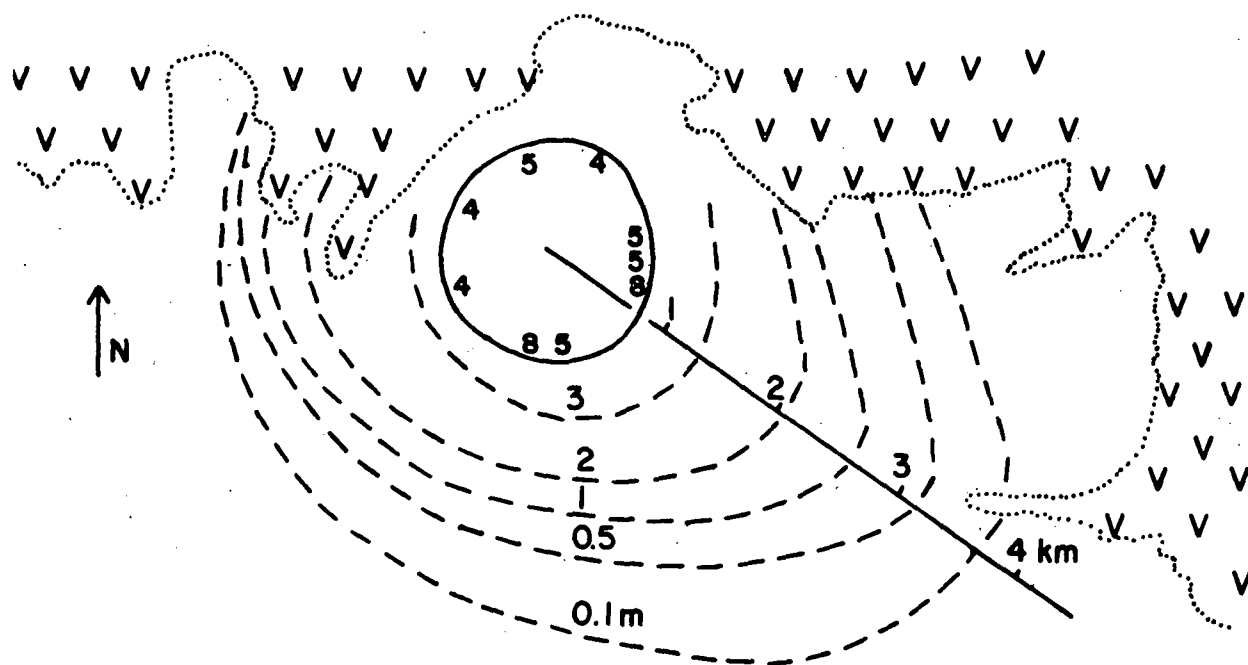


Figure 21. Schematic diagram showing variations of the violence of eruptions with time.



V V Paulina Basalt Flow No. 3
 --- Line of equal max. diameter
 of ejected blocks

Figure 22. Isopleth map of ejecta from Hole-in-the-Ground.

a westerly wind. If a slight wind had transported fine-grained ejecta to the southeast the large blocks would not have been affected and the isosizes would be circular. Had very strong winds produced the slight deviation for the isopleths, the fine ejecta would have been affected much more and very elongated isopachs would have resulted. Evidence thus indicates that the eruptive conduit was elongated in a northwest-southeast direction or, more probable, was inclined, producing vertical to slightly southeasterly inclined eruptions. As pointed out already, the isopleth map suggests that the axis of eruptions which deposited the main horizons deviates about 20° to 30° from the vertical toward the southeast. It is quite possible, however, that the eruption clouds reached greater heights where strong winds were blowing, so that fine dust may have been distributed over a larger area. Even though no field evidence has been found for such a distribution.

The isopach map mostly represents the distribution of the fine-grained material and shows the rim on the northwest side to be only half as thick as it is on the southeast side. We therefore deduce that not only were the major eruptions inclined but also the intermediate ones which laid down the bulk of the debris on the rim.

Since wind was excluded as a factor influencing the distribution of pyroclastic debris, the deposition of fine-grained material several miles from the center of the crater must be explained. Air drag causes small particles to fall out almost vertically. The eruption clouds must therefore have been of mushroom or cauliflower type, or a combination of both. However, a small amount of fine-grained material may have been deposited by horizontally-spreading base surges.

VOLUME OF EJECTA ABOVE PRE-ERUPTION SURFACE

The area covered by ejecta within the 0.2 m. isopach is about 36 km^2 . If the zero isopach encloses a total area of 100 km^2 , a volume of about 0.125 km^3 is obtained for the ejected mass. This is increased to 0.13 km^3 if 200 km^2 is assumed for the zero isopach. If the density of eruption products is taken as 2.0 g./cm^3 , as found from gravity measurements, the mass of the ejecta, taken as 0.125 km^3 , totals $2.5 \times 10^{14} \text{ g}$. The mass distribution in relation to the crater radius is shown in Fig. 26. Half of the ejected mass lies within 1.45 radii and about 90% within 3 crater-radii.

SUBSURFACE GEOLOGY BASED ON EVIDENCE FROM DRILL-HOLES

Two holes were drilled inside the crater during the summer of 1969, to gain information on the subsurface geology. As may be seen on the map (fig. 7), Hole No. 1 was drilled on the western slope of the crater to penetrate part of the unexposed sequence of the wall and to compare the wall rocks with ejected blocks. The hole was started 18.5 m. (61 feet) above the crater floor and 29.5 m. (97 feet) below the lowermost outcrop in the crater wall, i.e. at the base of the upper ignimbrite. The second hole, Hole No. 2, was started 12 m. (39 feet) lower than Hole No. 1 and 90 m. closer to the center of the crater, and about 7 m. (22 feet) above the crater floor. Its purpose was to penetrate the wall rock closer to the center and thus to determine the inclination of the wall. Knowledge of the stratigraphy of the wall rocks and the shape of the vent would then make it possible to estimate the volume of pyroclastic debris inside the vent.

Both drill-holes on the western slope were located so as to have the

Table 5: Log of drill-hole No. 1

Rocktypes		Thickness	Cumulative Depth	Remarks
Pumice		2'	2'	
Blocks	of fine-grained basalt (type 5)	12'	14'	Very hard to drill
Tuff		7'	21'	
Block	of fine-grained basalt (type 5)	10'	31'	very hard to drill
Tuff	some small blocks a few cm. in diameter between 31' and 40'	16'	47'	
Block	of Porphyritic basalt (type 3)	1'	48'	
Tuff		7'	55'	
Block	of Porphyritic basalt (type 3)	2'	57'	
Tuff		26'	83'	
Block		1'	84'	
Tuff		2'	86'	
Block	of fine-grained basalt (type 5)	4'	90'	very hard to drill
"Sediments"		50'	140'	
Ignimbrite		2'	142'	color: partially black, hard to drill
"Sediments"		23'	165'	
Ignimbrite		5'	170'	color: red, hard to drill
"Sediments"		5'	175'	
Ignimbrite	<u>Lower Ignimbrite welded from 205'-242'</u>	88'	263'	yellowish and pumiceous from 175' to 198', circulation lost at 198', cavity from 198' to 200' slow drilling from 205' to 242', <u>core: 231' to 233'</u>

Rocktypes		Thickness	Cumulative Depth	Remarks
Basalt	<u>Olivine-basalt</u> (type 4)	20'	283'	<u>core</u> : 267' to 270'
Scoria?		4'	287'	
"Sediments"		11'	298'	a few hard, thin layers of small blocks in a softer matrix
Basalt	<u>Highly porphyritic basalt</u> (type 3)	62'	360'	scoriaceous ? 298' to 300', <u>core</u> : 330' to 335', scoriaceous ? 357' to 360'
"Sediments"		15'	375'	
Basalt	<u>Highly porphyritic basalt</u> (type 3)	51'	426'	<u>core</u> : 392' to 395.5' 416' to 426'
"Sediments"		8'	434'	
Basalt	<u>Highly porphyritic basalt</u> (type 3)	45'	479'	circulation lost: 465', circulation regained: 472'
"Sediments"		5'	484'	
Basalt	<u>Highly porphyritic basalt</u> (type 3)	83'	567'	scoriaceous ? : 484' to 485; <u>core</u> : 510' to 515'. scoriaceous ? : 515' to 529', (may-be two flows with same drilling speed)

Table 6: Log of drill-hole No. 2

Rock-types		Thickness	Depth Total	Remarks
Pumice		2'	2'	
Tuff		10'	12'	includes a few feet of lakebeds - (reworked tuffs)
Block	Basalt	8'	20'	
Tuff	contains small blocks a few cm. in diameter at 95' and 100'	109'	129'	water-table intersected at depth of 65'
Block	Basalt (types ?)	1'	130'	hard to drill
Tuff	small blocks at 151', 160', 187' to 191', 208' to 209'	86'	216'	
Block	Basalt, type 5	0.5'	216.5'	very hard to drill
Tuff	some small blocks at 220-222', 242-243', 250', 260-261'	60.5'	277'	
Block	highly porphyritic basalt, type 3	8'	285	
Tuff	small blocks at 287' and 310'	37'	322'	circulation lost at 295' regained at 313', and lost at 329'
Block	highly welded ignimbrite	9'	331'	
Tuff		8'	339'	
Block	basalt (type 5?)	1'	340'	hard to drill
Tuff		1'	341'	
Block	basalt	2'	343'	
Tuff		1'	344'	
Block	basalt	0.5'	344.5'	

Rock-types		Thickness	Depth Total	Remarks
Tuff		3'	347.5'	
Block	basalt	1'	348.5'	
Tuff		2'	350.5'	
Block	basalt	4'	354.5'	
Tuff		1'	355.5'	
Block	basalt	2'	357.5'	
Tuff		2'	359.5'	
Block	basalt	10'	369.5'	
Tuff		0.5'	370'	

least influence of the northwest-southeast-trending fissure where the eruptions were presumed to have started. In addition, their location was chosen to straddle the ring-shaped gravity maximum, to be discussed later.

Hole No. 1 was abandoned at a depth of 173 m. (567 feet) and Hole No. 2 at a depth of 113 m. (370 feet). As long as water circulation could be maintained, cuttings were sampled every 5 feet. Lavas and one ignimbrite penetrated in Hole No. 1 were sampled by means of intermittent coring. It was also intended to core the bottom of Hole No. 2, but this was prevented by collapse of the wall of the hole. Changes of drilling speed were noted and related to changes in rock types.

In Hole No. 1, the water-table was intersected at a depth of 32 m. (106 feet); in Hole No. 2, at a depth of 20 m. (65 feet). The present water-table therefore lies only 13.5 m. (44 feet) below the lowest point of the crater floor or at an elevation of 1306 m. (4286 feet) above sea level.

Hole No. 1

A detailed log of Hole No. 1 is given in table 5.

Description of cores:

Core No. 1: 231' to 233', lower ignimbrite; recovered length 20 cm., diameter of core 6.5-7 cm. The ignimbrite is a dark violet, highly welded rock containing small inclusions of intermediate and felsic rocks. The core includes a fiamme 3 cm. long, 1.5 cm. wide and 0.4 cm. thick (refractive index 1.498 ± 0.002). The rock has a horizontal foliation due to welding.

In thin section the dark brown largely devitrified glass is seen to contain pale green clinopyroxene up to 0.3 mm. in length, plagioclase laths 0.1-1.5 mm. long, and a few needles of apatite.

Core No. 2: 267' to 270', olivine basalt (type 4); recovered length 62 cm., diameter of core 6.5-7 cm. The basalt is gray and contains some vesicles up to 2 cm. in diameter, and plagioclase and olivine phenocrysts up to 1 cm. in size.

A thin section shows phenocrysts of zoned sodic labradorite and rounded olivine in a groundmass of calcic andesine laths, augite grains, and ore. Interstitial glass makes up about 3% of the total volume.

Core No. 3: 330' to 335', dark gray porphyritic basalt (type 3); recovered length 70 cm., diameter of core 5.5 cm. The basalt shows flattened vesicles up to 2 cm. in diameter.

A thin section shows olivine phenocrysts up to 3 mm. in size (6%) which are in part iddingsitized. About a third of the rock is composed of normally and reversely zoned phenocrysts of sodic labradorite up to 1 cm. in size. Clinopyroxene ($2V_z = 48^\circ$), in part ophitic, takes about a fourth of the volume. Groundmass plagioclase, sodic labradorite to calcic andesine, makes up approximately 30%. The remainder consists of opaque oxides and about 1% glass.

Core No. 4: 392' to 395.5', porphyritic basalt (type 3); recovered length 90 cm., diameter of core 5.5 cm. The light gray basalt is dense and contains few vesicles. The large phenocrysts of plagioclase are oriented horizontally.

In a thin section phenocrysts of olivine (5%, is partly corroded and slightly iddingsitized) and zoned sodic labradorite (about 35%) are contained in a groundmass of labradorite-andesine subophitic augite ($2V_z = 48^\circ$), magnetite and ilmenite, accessory apatite and a little opaque glass.

Core No. 6: 510' to 515', porphyritic basalt (type 3); recovered length 80 cm., diameter of core 5.5 cm. The basalt is very vesicular, nearly scoriaceous. The groundmass is very dark or slightly reddish due to oxidation. The plagioclase phenocrysts are slightly smaller than in the other cores of type 3, and many are angular fragments of larger crystals. In the upper part of the core the phenocrysts are oriented horizontally, in the lower part there is no distinct orientation. The phenocrysts make up about 30% of the volume and consist of zoned sodic labradorite. The groundmass contains flow oriented plagioclase and small grains of augite, olivine and ore minerals.

The horizontal orientation of the vesicles of basalt cores and the flat-laying foliation of the ignimbrite indicate that the rocks penetrated by Hole No. 1 are still in their original horizontal position. The exact depth of the contact between the tuffs and wall rocks is not known, but it is below 27 m. (90 feet), where the lowest basalt block was penetrated, and above 49 m. (160 feet), where particles of ignimbrite appear and increase in frequency in the cuttings. Cuttings between 27 m. and 49 m. contain only a few fragments of porphyritic basalt, which presumably were incorporated from higher levels during circulation, but there were also many fragments of a fine-grained, vesicular basalt that cannot be correlated with certainty with any of the ejecta types. They were probably derived from sedimentary horizons containing basaltic debris. Similar beds are known from the section through the Peyerl Tuff unit along Highway 31, described earlier. The contact between the tuffs of the Hole-in-the-Ground eruption and the wall rocks is therefore taken to be at a depth of 27 m.

The tuffs which overlie the wall rock in Hole No. 1 contain large blocks, the largest being 4.1 m. in diameter. Two large blocks were encountered in the upper 10 m. and presumably were deposited at a late stage by rolling down from higher slopes of the crater wall.

The volcanic sediments and the ignimbrite from a depth of 27 m. to 80 m. are part of the Peyerl Tuff unit. The total thickness of the Peyerl Tuff unit, measured from the top of the upper ignimbrite in the crater rim to the top of the first lava in Hole No. 1 is therefore 125 m., closely agreeing with Hampton's (1964) value of 122 m. The basalt lavas underlying the Peyerl Tuff unit in Hole No. 1 would then correspond to Hampton's Hayes Butte Basalt. However the basalts underlying Hole-in-the-Ground are much thicker than indicated by Hampton.

Two types of basalt can be distinguished in the drill-hole, one being 8 m. thick and light gray, porphyritic, and olivine-bearing, the other being highly porphyritic and, together with 5 thin interbeds, leaving a thickness of 82 m. The olivine-bearing basalts can be compared to the light gray porphyritic olivine basalt (type 4) of the ejecta, and the highly porphyritic basalt represents the source of the porphyritic basalt (type 3) of the ejecta. The frequency of the porphyritic ejecta (type 3), (46%) thus corresponds to a thickness of the lavas exceeding 82 m. This agrees well with the estimate given earlier, namely 92 m.

The fine-grained, light to medium gray basalt (type 5) found in the ejecta with a frequency of 23% was not penetrated in Hole No. 1. Presumably, it underlies the porphyritic basalt. Its thickness can be estimated by considering the frequencies of types 3 and 5 and the thickness of the porphyritic basalt in the drill-hole, if the diameter of the vent is not

assumed to change between these lavas. The thickness of type 5 would then be at least 41 m. Type 6 of the ejecta, which makes up approximately 5% of the large ejected blocks, was also not penetrated. Its frequency in the ejecta corresponds to a thickness of about 9 m. Thus the total thickness of strata penetrated by the vent of Hole-in-the-Ground exceeds 300 m.

Hole No. 2

Drill-hole No. 2 was started 90 m. closer to the crater center than Hole No. 1 and was abandoned at a depth of 113 m. (370 feet). A detailed log is given in table 6.

In Hole No. 2, no wall rocks were penetrated, only tuffs and enclosed blocks. Judging from the cuttings, the tuffs do not differ materially from those in the crater rim. In the 113 m. thickness penetrated only 14.3 m. or 12.7% consist of blocks larger than 15 cm. in diameter, and most of these were in the lower 30 m. of the hole. The upper-most block, which was nearly 2.5 m. in diameter was only 4 m. below the surface, can be regarded as a block that rolled down from the upper slopes of the crater wall. Apart from this single large block the upper 87 m. of the material in Hole No. 2 consist mainly of fine-grained tuffs. In contrast, the tuffs in Hole No. 1 contain 10 m. of blocks with a total thickness of 30 m. or 33% of the volume.

Evaluation of results

If we assume that the wall rock was reached at the bottom of Hole No. 2, the slope of the wall between both drill-holes would be 48° . If the wall is at any greater depth, the angle of slope must be steeper. The slope between the lowermost outcrop in the crater wall and Hole No. 1 is 40° ; thus the slope between the two drill-holes increases toward the center of the crater.

Since the crater is large and cuts strong lavas and ignimbrites, it seems unlikely that the slope is steeper than 50° within the depth range of the drill holes because there are too few blocks of rocks from these levels to account for a larger volume of the vent.

The form of the vent inferred from drilling results can be explained in several ways.

1. Eruptions left an open hole at least 300 m. deep which was later filled to the present depth by subsequent eruptions and erosion of the rim.
2. The vent has steep walls and a diameter of approximately 800 m., but much of the material in the vent was emplaced there during the eruption.
3. Arcuate and steep, inward-dipping slide planes led to a large-scale slumping of wall rocks and overlying ejecta. The present contact could have been the base of a slump block, in which case the original crater was much deeper but narrower than the present one.
4. Subsidence along a ring-fault produced part of the crater and the contact between tuffs and wall rocks between Holes No. 1 and No. 2 is nearly vertical; as in case 3, the original crater was narrower and its depth was presumably greater than that of the crater.

The first case can easily be excluded since it requires that very large amounts of country rocks were ejected at an earlier stage. The total volume of ejecta outside the crater should then be much larger than it is. (This model would also pose the problem of how such a large crater was formed in the first place.)

The second possibility would require that during the eruptions gas-flow was active in a vent-area with a diameter of 800 m. To produce the great

velocities of the ejected blocks, a high orifice-pressure is required. The larger the orifice and the shallower the eruption focus the lower would be the ejection velocities. The eruption focus at Hole-in-the-Ground can be assumed to be at a depth exceeding 300 m. Even if it was at a depth of 500 or 1000 m., the depth-to-diameter ratio would still be only 0.6 to 1.25, i.e. the vent would have been nearly as deep as wide. It is likely that channeling due to uneven gas-flow would start very soon, restricting flow to a smaller cross section. However, channeling largely stops the processes of widening of the vent. The lowermost ejecta in the rim of Hole-in-the-Ground indicate ejection-velocities of about 100 to 120 m./sec. Similar and even greater velocities prevailed during most of the eruption history. It appears, therefore, that the high ejection velocities are incompatible with an active vent of large diameter.

The third and fourth possibilities both involve rather similar volumes of rocks in the near-surface movements and thus cannot be distinguished on this basis. The major difference concerns the attitude of the boundary-plane and the role of rocks of deeper levels. Deeper horizons would only be affected by subsidence along a ring-fault but not by near-surface phenomena of slumping. Slumping is more likely to occur in weak rocks at shallow depths.

If the porphyritic basalt and overlying wall rocks slumped into a cylindrical vent with a diameter of 300 m., the volume relation would require an open vent at least 400 m. deep. If the diameter of the vent was smaller, the open vent must have been correspondingly deeper. Slumping usually occurs on concave planes the dips of which decrease downward. At

Hole-in-the-Ground, however, the dips increase inward, perhaps because of the effect of decreasing diameter and the influence of joints in the basaltic flows. Repeated slumping and subsidence would be very effective in closing the vent and restoring pressure to produce the cyclic activity indicated by the rim deposits.

If we assume subsidence along a steep ring-fault, we must account for the fact that about 90% of the ejecta blown out during the eruptions consist of country rocks. Only repeated subsidences could account for the nearly uniform conditions at the eruption foci which are reflected in similar ejection velocities during most of the eruptions. Repeated subsidence may have taken place into space from which the magma has been drawn during the entire course of the eruption, but this process is hard to reconcile with the small volume of juvenile ejecta which is only about one third of the volume of the crater below the original surface.

Considering all the available information it is difficult to make a definite choice between these alternate mechanisms; both slumping and subsidence yield similar surface expressions. We believe, however, that both probably operated to some extent, and subsidence along a ring-fault was the most important.

VOLUME OF PYROCLASTIC DEBRIS BELOW THE FLOOR OF THE CRATER

The volume of the crater below the original surface, V_c , was found to be about $0.77 \cdot 10^{14} \text{ cm}^3$ or only 61.5% of the volume of the ejecta, $V_e (1.25 \cdot 10^{14} \text{ cm}^3)$. If the average density of the ejecta, ρ_e , is about 2.0 g/cm^3 and the average density of the country rocks, ρ_c , is about 2.3 g/cm^3 , there is a mass deficiency of:

$$\Delta M = V_e \rho_e - V_c \rho_c = 1.25 \cdot 10^{14} \cdot 2.0 - 0.77 \cdot 10^{14} \cdot 2.3 = 0.73 \cdot 10^{14} \text{ g.}$$

It is reasonable to assume that low density material below the crater floor accounts for this deficiency.

If only country rock had been involved in the eruption, i.e. if the eruption was purely phreatic, an estimate could be made of the volume of the low density material below the crater floor. The volume of the ejecta recalculated to a density of 2.3 g/cm^3 would be 0.109 km^3 . If only this volume had been ejected and no account were taken of the feeding pipe, the volume of the crater would also be 0.109 km^3 . The fact that the actual crater volume is only 0.077 km^3 can be explained by the decrease in density of the underlying material. The decrease in density due to brecciation leads to a volumetric increase and corresponding decrease of the crater volume. The volume of the material still within the pipe, V_b , can therefore be calculated using the formula

$$V_b = \frac{V_e \rho_e - V_c \rho_c}{\rho_c - \rho_b}$$

ρ_c is the density of the brecciated material in the pipe. In this case ρ_b is assumed to be the same as ρ_e . V_b is therefore 0.243 km^3 and M_b the mass of the low density material in the pipe, would be $4.86 \times 10^{14} \text{ g}$. The volume of this low density mass would be sufficient to explain the "phreatic" mass deficiency calculated above. If ρ_b is larger than ρ_e due to compaction or a higher content of large, unbrecciated blocks, V_b will also be greater.

Addition of juvenile material must also change the volume relationships. The volume of breccia in the pipe then becomes:

$$V_b = \frac{V_e \cdot \rho_e \cdot (1 - \gamma) - V_c \cdot \rho_c}{\rho_c - \rho_b \cdot (1 - \gamma)}$$

where γ is the amount of juvenile material expressed as a fraction of V_e . The density of the juvenile material is assumed to be the same as the density of the ejecta, i.e. 2 g/cm^3 , which is a reasonable value in view of its vesicularity. If $\rho_b V = \rho_e$ and $\gamma = 0.1$ V_b is $0.96 \cdot 10^{14} \text{ cm}^3$ or 0.096 km^3 . (If $V_e = 0.132 \text{ km}^3$ V_b is 0.122 km^3).

A "phreatomagmatic" mass deficiency can now be defined that takes into account the juvenile fraction:

$$\Delta M = V_e \cdot \rho_e \cdot (1 - \gamma) - V_c \cdot \rho_c$$

For the given values ΔM would be $0.48 \cdot 10^{14} \text{ g}$.

These calculations are based on several assumptions. The first is that there has been no intrusion of juvenile material to displace the vent breccia. Secondly, spalling or subsidence of large slabs of country rock into the marginal parts of the pipe, assuming their density is not changed, would increase the dimensions of the pipe without being reflected in the volume relationships. Slumping of the crater walls would not have affected the volume relationships but would only have changed the shape of the crater.

If subsidence took place and the whole vent filling and parts of the wall rocks subsided into the part of the magma chamber evacuated by eruptions, the juvenile fraction would have to be treated as part of the country rock in order to calculate the proper subsurface volume. If subsidence was related to evacuation of the magma chamber by eruptions coupled with subterranean migration of magma, calculations would depend very much on how much space

was provided by the latter. If subterranean migration was relatively small, as can be assumed at Hole-in-the-Ground, V_b would lie somewhere between the values determined by calculation with and without juvenile contribution.

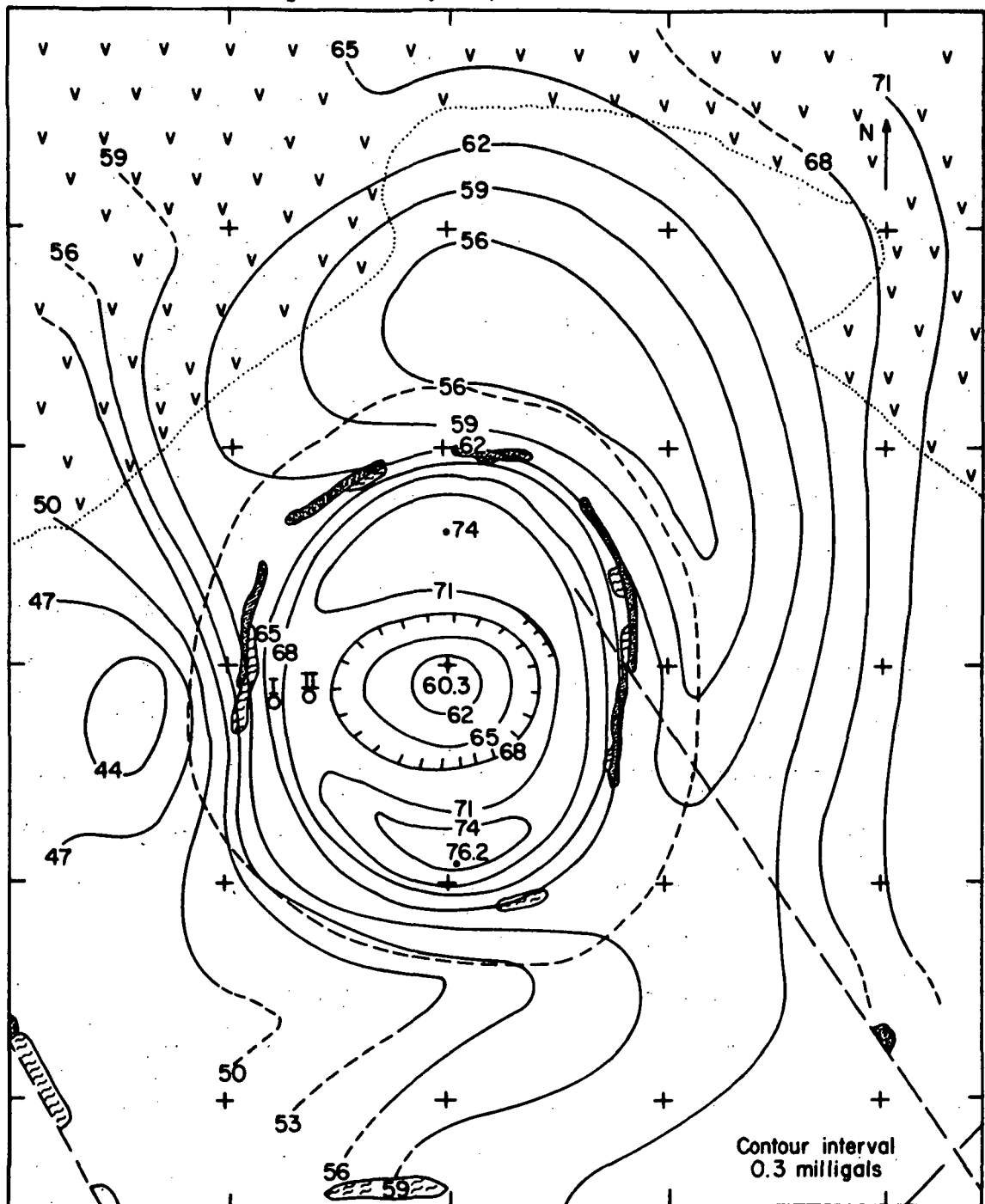
If we assume that the subsurface structure at Hole-in-the-Ground is approximately rotation-symmetrical we can use the drilling results to get an independent estimate on the subsurface volume. For that purpose we extend the slope of the wall rocks from Hole No. 1 to the bottom of Hole No. 2 and then toward the center of the pipe to a minimum depth of 300 m. in order to have a cone-shaped structure with the tip of the cone in the center at a depth of 300 m. The volume of the pyroclastic debris inside this cone is then approximately 0.1 km^3 , and its mass calculated for a density of 2.0 g/cm^3 is $2.0 \times 10^{14} \text{ g}$. The value of 0.1 km^3 closely corresponds to the value of 0.096 km^3 calculated independently above. It is quite certain, however, that the actual value substantially exceeds the estimated minimum value of 0.1 km^3 , and may be perhaps 0.13 to 0.15 km^3 . This larger volume would then agree with the assumption that the crater was partly formed by repeated subsidence due to subterranean withdrawal of magma.

GEOPHYSICAL RESULTS

The results of gravimetric and geomagnetic measurements undertaken by Kim (1968) are shown in fig. 27-30. Interpretations of the gravimetric measurements should be considered preliminary and only of qualitative value.

The residual gravity profiles show a negative anomaly on the crater floor and relatively high anomalies along the inner crater wall. The anomaly

Bouguer anomaly map of Hole-in-the-Ground



- v v v Paulina Basalt flow, No. 3
- Paulina Basalt flow, No. 2
- ~~~~~ Peyerl Tuff: upper ignimbrite
- - - - - Crater rim
- _____ Fault
- I, II Drillhole No. I, No. II

Bouguer anomalies from C.K. Kim (1968)

Figure 27. Bouguer anomaly map of Hole-in-the-Ground.

below the crater floor is higher than the values outside the crater. There is also a ring-shaped maximum of approximately 2 mgals. along the crater wall and between the two drill-holes.

The following interpretation is given by Kim (personal communication). If the vent has a simple cone-shape and were filled only with low-density tuff it would be impossible to explain the observed gravity values inside the crater wall. There should be a positive density contrast in the interval between the two drill-holes. It is postulated, therefore, that an igneous intrusion of some sort is responsible for the gravity high.

The thickness of a ring-dike that would produce the observed gravity effect can be calculated from Nettleton's (1942) vertical sheet formula. The thickness of more than 300 m. obtained by this method seems far too large, since it would hardly leave space for a vent. Moreover, the negative gravity effect of the low-density vent-filling should be less than that of the undisturbed rock on the outer side of the dike. There would have to be a dense intrusion at depth to balance the effect of the low-density material in the vent and the central gravity low would be at a higher level than the value outside the crater.

It is possible to use Nettleton's (1942) method to calculate the maximum depth of the center of a sphere that would produce a gravity amplitude of 2.4 mgals. For this model the two positive maxima of the gravity curve are assumed to be continuous with no effect from the low-density vent filling. The maximum depth obtained is 610 m. The gravity effect of a sphere is a close approximation of a diapir or plug. The calculated effect of a series of circular discs is a gravity curve that

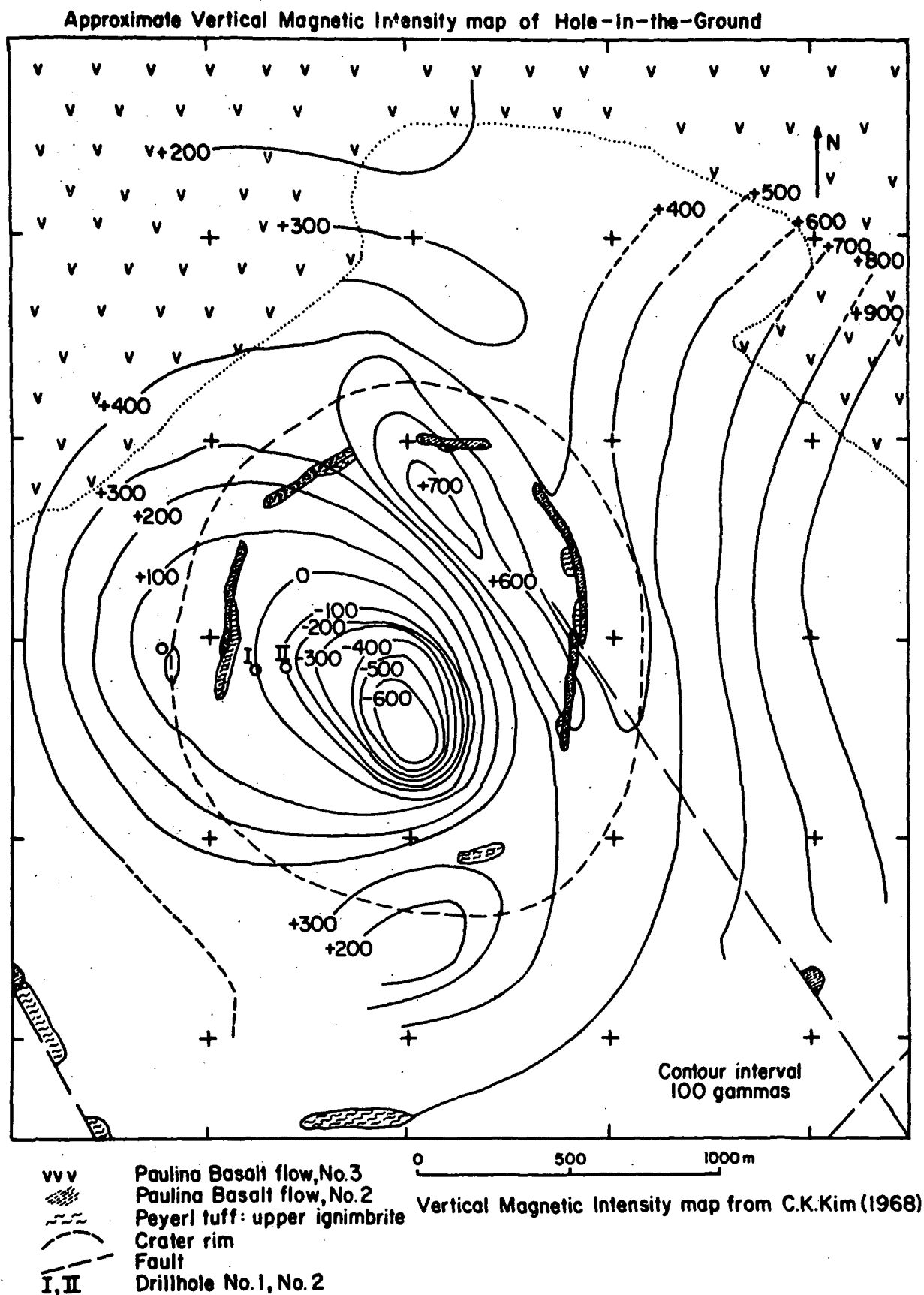


Figure 28. Vertical magnetic intensity map of Hole-in-the-Ground.

does not envelop the positive maxima completely. The difference between the observed and calculated gravity values can best be explained by a combination of a dense ring-dike, 60 m. thick extending from an intrusive plug upwards to a depth of 150 m. below the crater floor (fig. 9). The crater floor is probably underlain by low-density tuff inside a ring-dike that rises from a dome-like intrusion at depth.

The structure postulated from the gravimetric interpretation (fig 9) could have resulted when a rising plug of basalt magma came into contact with ground-water and produced a phreatomagmatic eruption. Periodic subsidence along a ring-fault resulted partly from the eruption of large amounts of wall rock and partly from subterranean withdrawal of the magma. Renewed inflow and intrusion along the ring-fault produced the present substructure.

The results of Kim's (1968) vertical magnetic intensity survey are shown in fig. 28-30. The map (fig. 28) shows a large negative anomaly of about 600 gamma near the southwest part of the crater floor and a marked eastward gradient. This negative anomaly indicates material of low magnetic susceptibility beneath the crater floor. It corresponds to a gravity anomaly produced by low density material in the same area. This material of low density and low magnetic susceptibility must be tuff and breccia filling the pipe.

The negative magnetic anomaly is elongated in a northwesterly direction and coincides with the large diameter of the crater. The same trend is indicated by the SE lobes of both isopachs and isopleths of the ejecta blanket. These features suggest that the pipe is elongated in southeasterly direction and the eruptions were inclined in the same direction. The negative

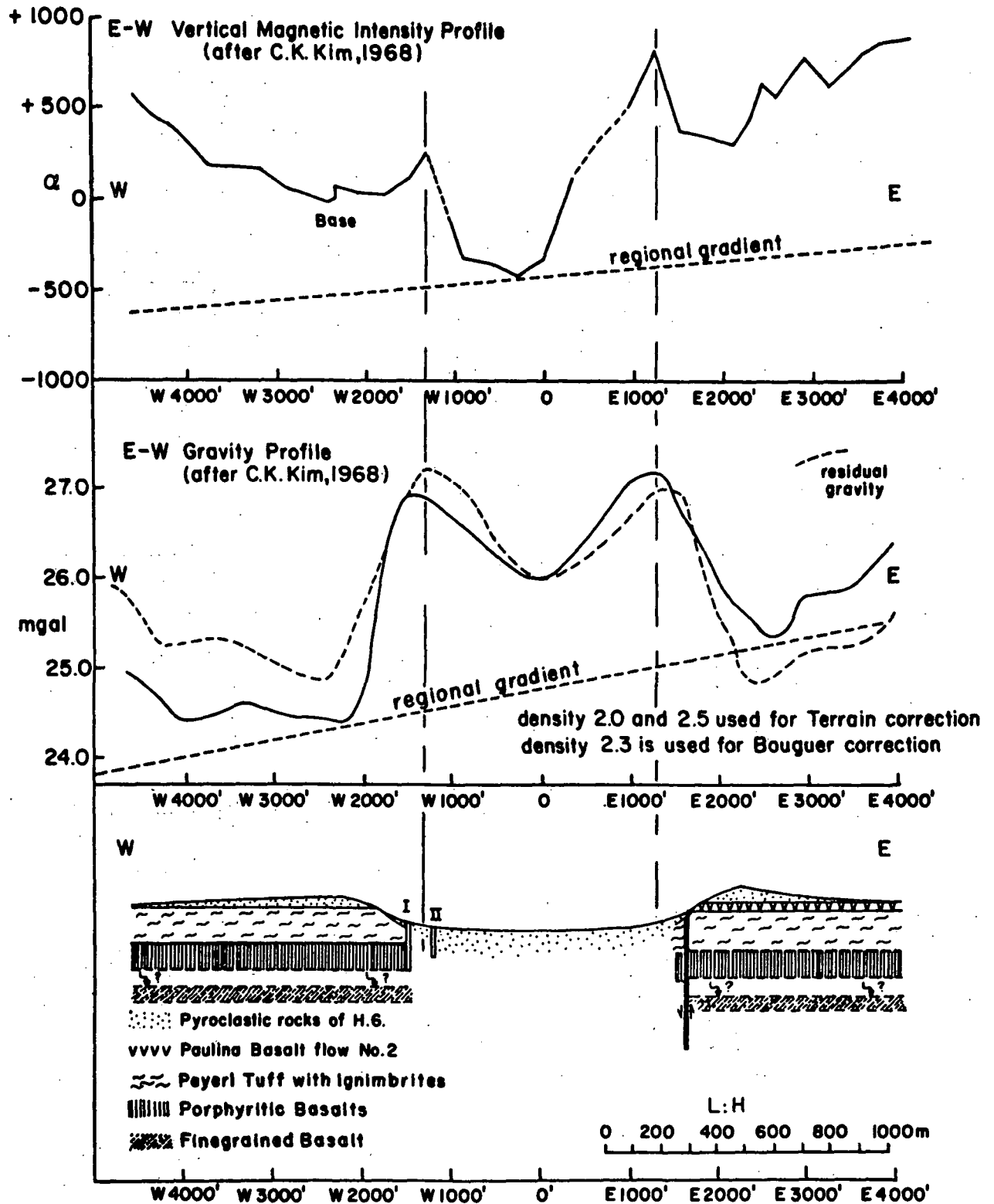


Figure 29. Geomagnetic, gravimetric and geological section through an east-west profile of Hole-in-the-Ground (after Kim, 1968).

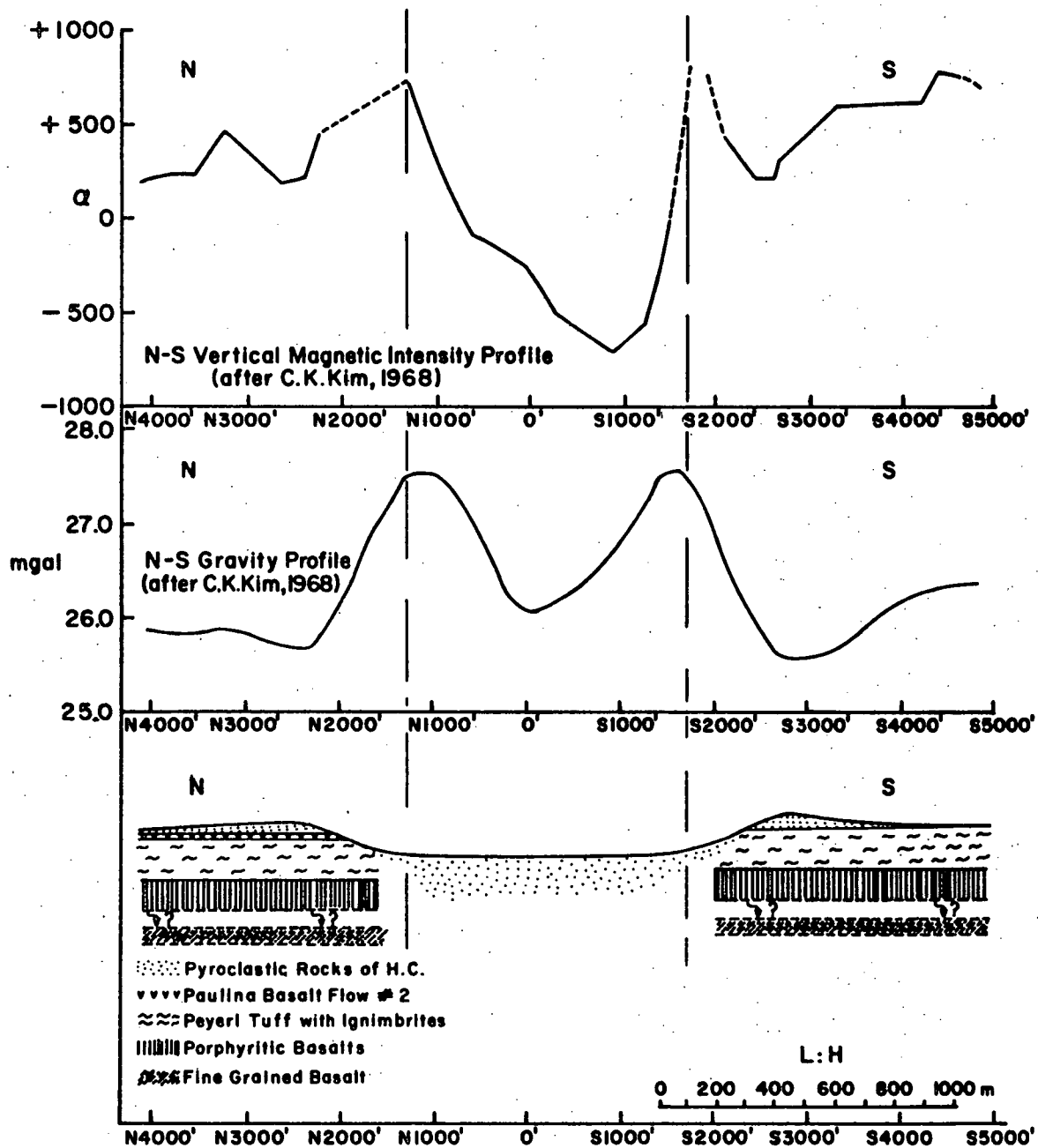


Figure 30. Geomagnetic, gravimetric and geologic section along a north-south profile through Hole-in-the-Ground. (After Kim, 1968).

anomaly in the southwestern part of the crater floor probably represents a thicker part of the pipe.

Since the magnetic effect of a buried feature is inversely proportional to the square of its depth, small magnetic variations near the surface can produce an anomaly comparable to that of a larger body at a deeper level. The vertical magnetic intensity increases from the crater floor up the wall nearly up to the ignimbrite and Paulina Basalt outcrops then gradually drops to the crater rim. The anomaly near the ignimbrite and Paulina Basalt may be due to the high magnetic susceptibility of both units. It is more likely however, that the anomaly is the result of the ring-dike intrusion indicated by gravimetric results. The lower values at the rim of the crater are due to the thick layer of weakly magnetic tuff. Steadily increasing magnetic values outward from the rim probably result from the thinner ejecta blanket and the shallower depth of both the ignimbrite and Paulina Basalt.

In summary, an evaluation of the geophysical measurements indicates that:

1. A northwest-trending elongated pipe beneath the crater is filled with low-density material down to a depth of several hundred meters.
2. A domical intrusion occupies the lower part of the structure and extends upwards around its margins as a ring-dike.

Energy Requirements

Estimates of the kinetic energy necessary to eject the volume of 0.125 km^3 can be made from the relation: $E_{\text{kin}} = 1/2 m V_0^2$. If the initial ejection velocity, V_0 is taken as 200 m/sec. the kinetic energy is 5×10^{22} ergs or the equivalent of 1.2 megatons of TNT. This value is an upper limit because the initial velocity of 200 m/sec. is only associated with the eruptions that laid down the main horizons. Using 100 m/sec. as a more realistic average value, the energy requirements are reduced to 1.25×10^{22} ergs or 0.3 megatons of TNT.

A large part of the breccia must have been ejected only to fall back into the vent and be ejected again. If the volume of rock left in the vent were thrown out only once in the same manner as the ejecta in the rim, about 4.0×10^{22} ergs more energy would be required (for a velocity of 200 m. per sec. and a volume of 0.10 km^3). In addition, the energy required to lift the total volume from half of the depth of the pipe to the surface would be 1.1×10^{22} ergs for a depth of 500 m. The total energy required to lift the entire volume and eject it at a velocity of 200 m/sec. would be 10.1×10^{22} ergs. For an initial velocity of 100 m/sec., it would be 3.35×10^{22} ergs.

Energy was also consumed in disrupting and brecciating the country rock and juvenile magma, and in friction, turbulence, heat losses to the country rock and atmosphere, vaporization of water and to seismic shocks and atmospheric effects.

The estimated crushing energy derived by Innes (1961) for the Rainier nuclear test explosion (Johnson, Higgins, and Violet, 1959) is about 6.4×10^7 ergs/g. Since the Rainier nuclear device was buried in bedded tuffs

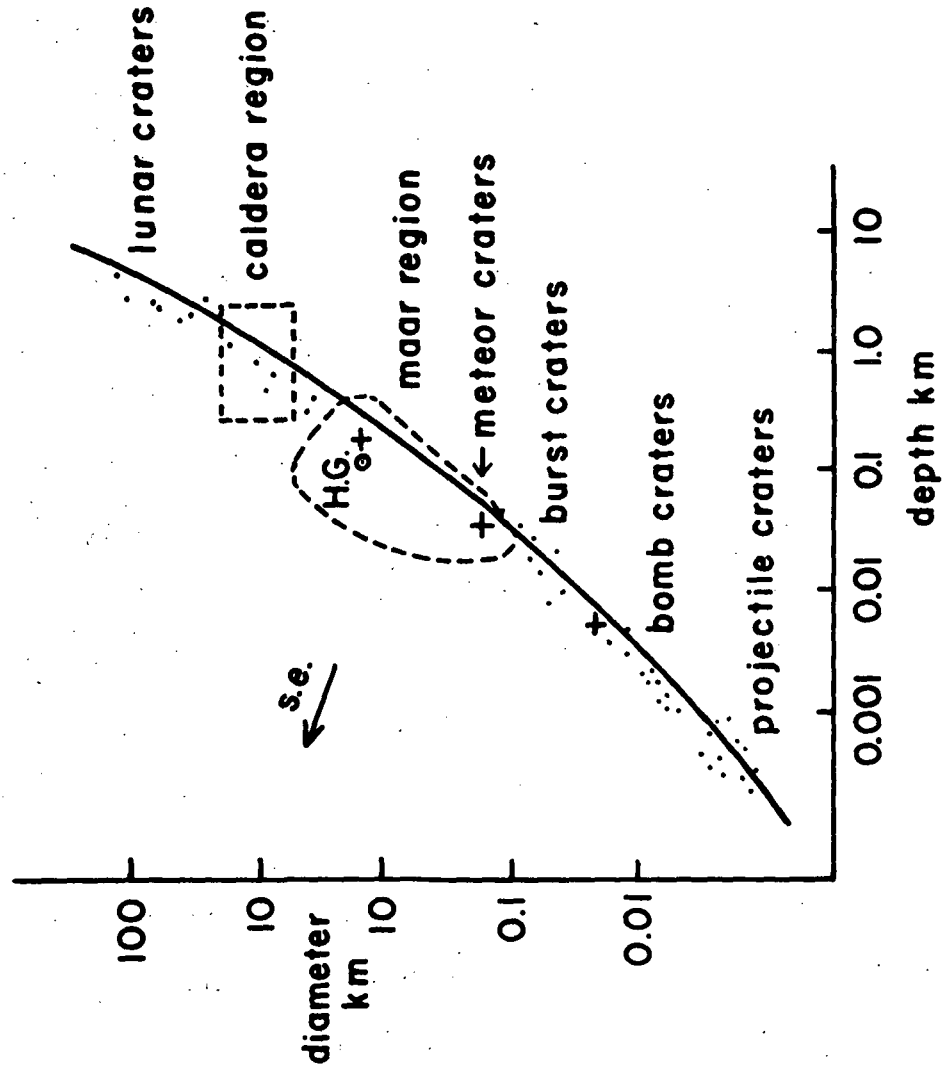


Figure 31. Depth to diameter relations of craters formed by various mechanisms.
(after Baldwin, 1949, and Steinberg, 1968)

with a density of 2.0 g/cm^3 this value is probably of the right order of magnitude for crushing the combined basalt, tuff, and sediment sequence below Hole-in-the-Ground. Innes (1961) also points out that about $2.7 \times 10^7 \text{ ergs/g.}$ are needed to crush average rock to 3 inch size and about $4.1 \times 10^8 \text{ ergs/g.}$ to pulverize it. Dockter, Belter and Ellman (1967) give figures for pulverizing lignite, a rock with properties close to those of weak tuffs and lake sediments. When lignite in a size range of 1/2 inch to 1/4 inch is pulverized in a ball mill, $5.08 \text{ to } 12.4 \times 10^8 \text{ ergs/g.}$ are consumed. For Hole-in-the-Ground, where a high proportion of the country rock is already fine-grained, a value of about $6.4 \times 10^7 \text{ ergs/g.}$ is more reasonable. For a total crushed mass of $4.5 \times 10^{14} \text{ g.}$ the crushing energy required would be about $2.88 \times 10^{22} \text{ ergs.}$

Sakuma and Nagata (1957, p. 997) state that the seismic energy of a volcanic explosion is less than the kinetic energy of ejecta by a factor of 10^{-2} to 10^{-4} . Decker (1961) studied the January 12, 1960 eruption of Anak Krakatau and concluded that for a single eruption the release of the seismic energy was less than the explosive energy by a factor of about 2×10^{-4} . The total seismic energy released at Hole-in-the-Ground would therefore have been in the range of 2.0×10^{18} to $9.0 \times 10^{20} \text{ ergs.}$

Since the energy expended by these various processes was derived from the heat of basaltic magma, it is interesting to examine the thermal energy released by cooling of juvenile material in the ejecta.

The total weight of the pyroclastic debris is about $4.5 \times 10^{14} \text{ g.}$ of which the juvenile fraction is approximately 10%, or $4.5 \times 10^{13} \text{ g.}$ Prior to quenching, the basalt was about 40% crystallized and at a temperature of approximately 1100° C. The heat of crystallization should be neglected

because the ejecta is largely glassy, but if the average heat capacity is $0.3 \text{ cal/g/}^{\circ}\text{C}$ and the basalt were quenched from 1100°C to 300°C it would release thermal energy amounting to about 4.5×10^{23} ergs or more than seven times the combined energy required to crush, lift, and eject the entire volume with an initial velocity of 100 m/sec. (6.23×10^{22} ergs).

The mechanical work was probably performed by expanding gas, mainly water vapor, following a relief of pressure. This water vapor could have come from the magma or it could result from heated ground water. The apparent density of the eruption clouds can be used to get a crude estimate of the weight of the water vapor involved in the eruptions. If 0.04 g/cm^3 is taken as the fluid density and 0.0395 g/cm^3 as the particle concentration at 100°C and 1 atmosphere for all the pulses of the eruption, the total weight of the saturated water vapor eruptions would be about 5.7×10^{12} g. This amount of water could not have been released from the juvenile basalt. Even if the basalt magma contained as much as 1 to 3 weight percent of water the total amount of basalt involved in the eruptions would contain only 4.5×10^{11} to 1.35×10^{12} g. of water, and only a small part of this could have been exsolved during the eruption. It seems more likely that groundwater was the principal source, as has already been indicated by other geological evidence.

To heat 5.7×10^{12} g. of water from 30° to 300°C and vaporize it would require 1.5×10^{23} ergs. In addition a large amount of heat energy would be lost to the country rock. Adiabatic expansion of 5.7×10^{12} g. water vapor from 1000 bars to 1 atmosphere would release approximately 2.5×10^{22} ergs and would not account for the mechanical work performed in the eruption. If, however, we consider the heat content of rock fragments carried in the gas,

a much larger reservoir of energy would be available. The effect would be for the vapor to expand nearly isothermally. Calculation of the work done by gas expanding under these conditions at 300°C gives approximately 1.2×10^{23} ergs, substantially more than the amount required. As Yokoyama (1956) points out, the actual value will lie between the adiabatic and isothermal values.

Considering the uncertainties involved in these estimates, it is not reasonable to expect precise agreement for the various factors we have compared. It appears, however, that the heat released by quenching the juvenile fraction of the pyroclastic debris is adequate to heat a volume of ground water and country rock for the vapor to perform the mechanical work of the eruption.

The strongest eruptions at Hole-in-the-Ground ejected about one percent of the total volume of pyroclastic debris or the equivalent of a layer about 40 cm. thick at the rim and amounts to a volume of $2.25 \times 10^6 \text{ m}^3$, and a mass of $4.5 \times 10^{12} \text{ g}$. The velocity of the strongest eruptions was taken as 200 m/sec. Since

$$E_{\text{kin}} = 1/2 m v^2$$

the kinetic energy of the strongest eruptions was about 9×10^{20} ergs or the equivalent of 21.4 kt TNT.

Romney (1959) gives an empirical formula for the correlation of the magnitude of a volcanic earthquake with the explosion energy of an eruption:

$$M = 3.65 + \log Y$$

where M is the magnitude of the earthquake and Y the energy of the eruption.

For Hole-in-the-Ground this gives a magnitude of 5. The seismic energy can

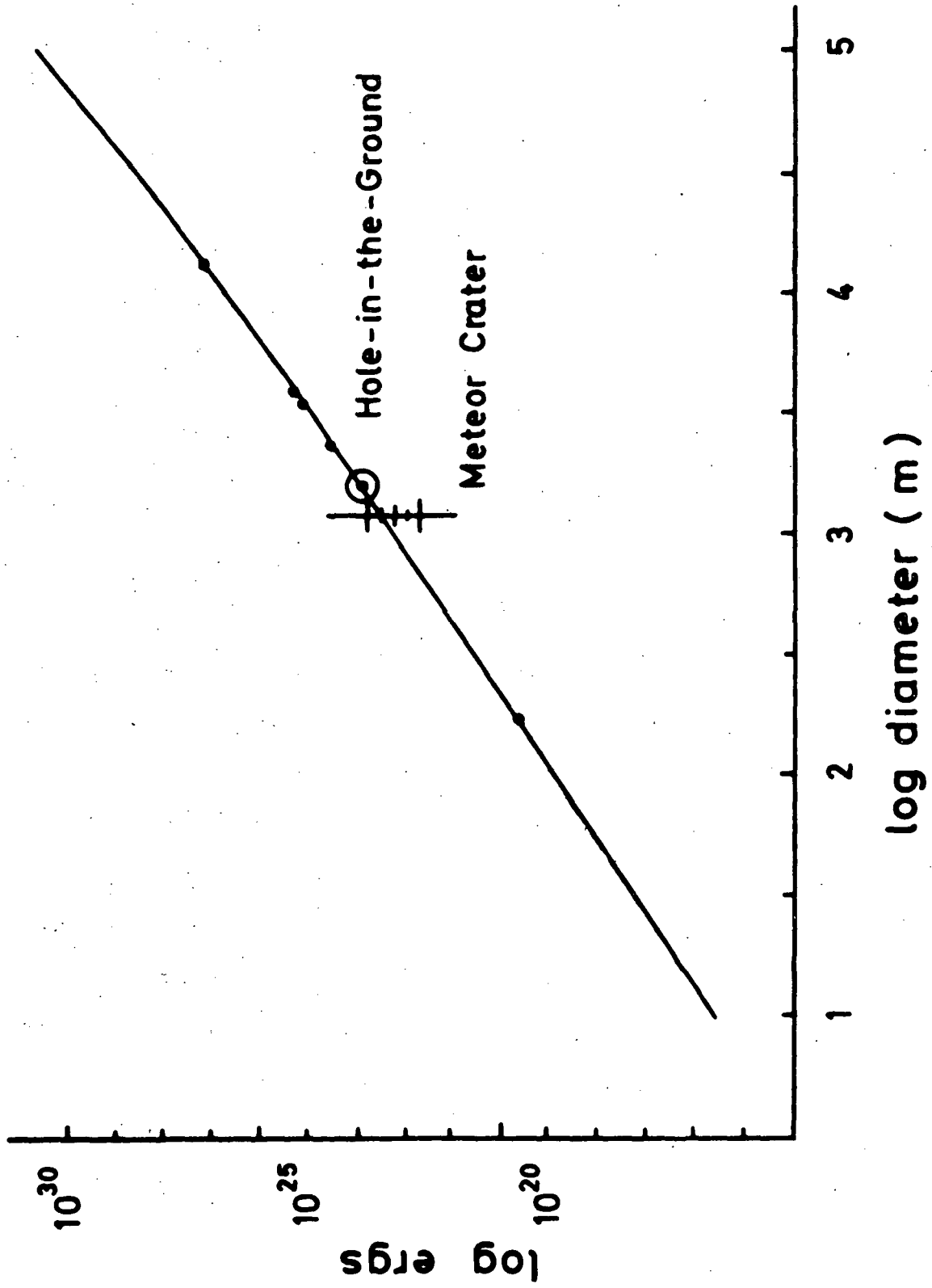


Figure 32. Relation between crater diameters and total available energy.
(after Baldwin, 1963 and 1969)

be calculated from Gutenberg and Richter's empirical formula (1956):

$$\log E = 9.4 + 2.14 M - 0.054 \times M^2$$

where E is the energy in ergs and M the earthquake magnitude. The seismic energy of the strongest eruptions at Hole-in-the-Ground was therefore 5.63×10^{18} ergs which is 6.2×10^{-3} of the kinetic energy of the eruptions.

Causes of the Eruption

The presence of sideromelane, accretionary lapilli, vesiculated tuffs in base surge deposits, and impact sags with undisrupted bedding all point to phreatomagmatic eruptions caused when rising basaltic magma came into contact with groundwater. Drilling results indicate that the eruption focus must have been at a depth of more than 300 m., approximately 240 m. below the groundwater-table at the time of the eruptions.

The eruptive activity was periodic, varying from moderate to very strong. Eruptions of intermediate strength, with maximum orifice pressures of about 230 bars were interrupted by major eruptions with pressures up to 540 bars. These variations seem to have been related to periodic intrushes of groundwater into the eruptive conduit, and similar to those that are believed to account for the 1924 steam-blast eruptions of Kilauea volcano (Finch, 1947; Jaggar, 1947).

The periodic activity and subsurface structure also point to repeated large-scale slumping or subsidence along a ring-fault which periodically plugged the vent. The vent cannot have been continuously widened without a large drop in the orifice-pressure and we have already noted that the pressures indicated for eruption of the main block horizons are nearly uniform. Subsidence and slumping of the wall rocks would have provided new material to be

thrown out with little need for a widening of the vent. Both processes influence the periodic inrush of groundwater, obstructing it at certain times and facilitating it at others.

If the average density of the country rock is 2.3 g/cm^3 the confining pressure increased from about 70 bars at a depth of 300 m. below the surface to 115 bars at a depth of 500 m. and 230 bars at 1000 m. Although the eruption pressures were in this range, there is no evidence that the conduit is more than 500-700 m. deep, and it appears that the high pressures at the eruption foci were not controlled by the load of overlying rock. Water heated at constant volumes exerts very high pressures on its walls, and it would be possible to explain the high pressures at the beginning of an eruption by such a mechanism. But once an eruption has started there would be little chance to attain such pressures again. Heatflow-measurements in the upper 170 m. of drill hole No. 1 indicate considerable movement of groundwater in the wall rock (J. H. Sass, personal communication). It is clear that the high permeability of the fractured wall rock would allow the pressure of water to be dissipated rapidly.

After an eruption, fallback of ejecta, subsidence, faulting, slumping, and defluidization of debris still in the conduit must seal the vent rather effectively. Ground water will enter rapidly from the neighboring wall rocks and through part of the vent breccia, because of the sharp depression of the water table which, at the time of the eruptions of Hole-in-the-Ground, was at least 240 m. above the eruption focus. The inrushing water would be heated and may build up pressure rapidly, especially

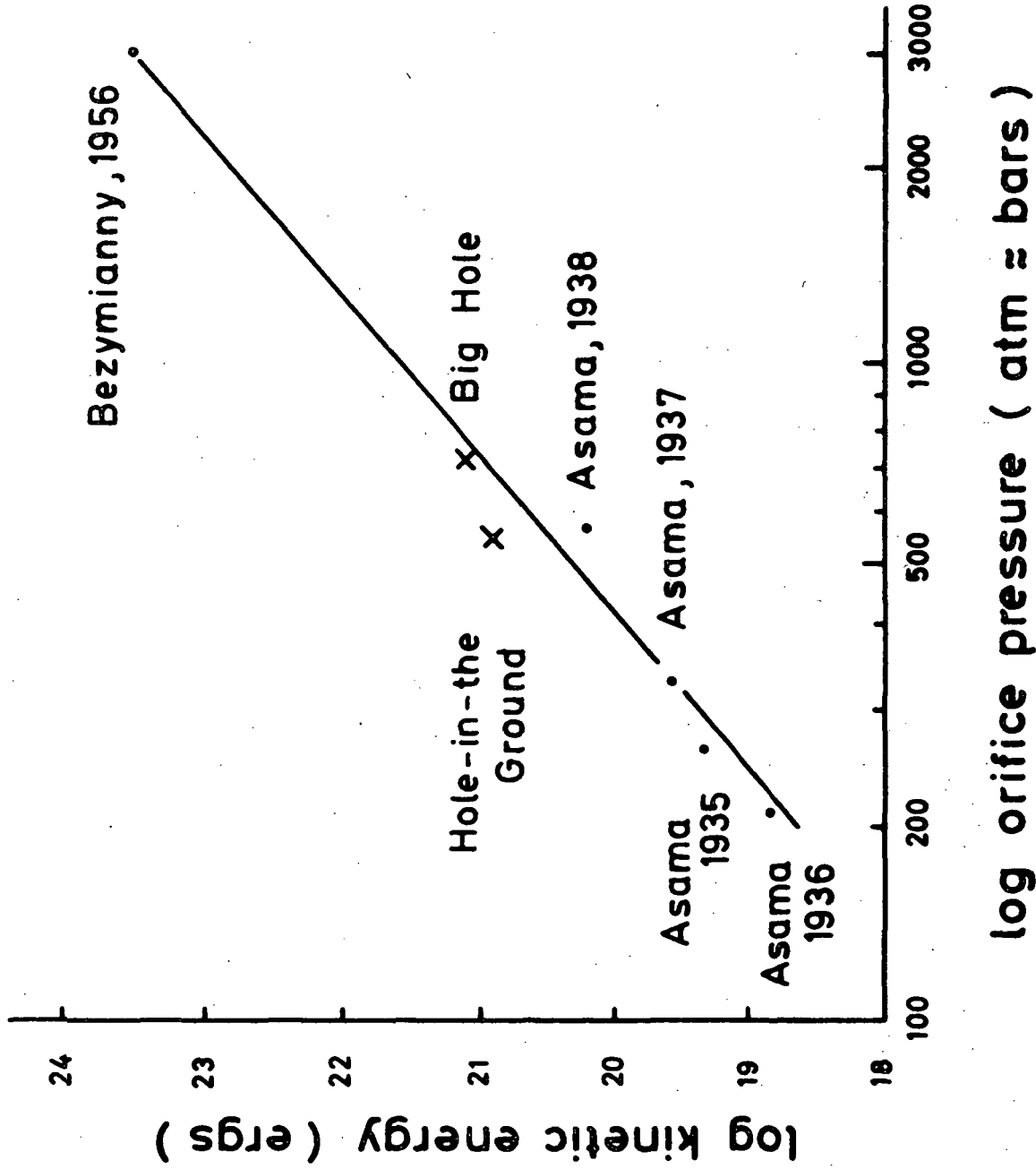


Figure 33. Relation between the kinetic energy of eruptions and orifice pressure.
(after Richards, 1965)

when the water is vaporized. Once the water is vaporized, however, it can move through the rock more readily, since the permeability of rocks for steam is much higher than it is for liquid water. This phase change could bring a relief of pressure and trigger another eruption. The system would be very sensitive to the rates of heating and pressure relief.

We conclude, therefore, that the repeated build-up of nearly uniform pressures indicated by the main block horizons corresponds to repeated cyclic events resulting from the inrush of ground water into breccia that fell back from a previous eruption, slumped into the vent from the walls or subsided along a ring-fracture.

Duration of the Eruptions

Knowing the ejected volume, the percentage of the juvenile fraction and the volume of pyroclastic debris still inside the vent, an attempt can be made to estimate the length of the eruption period. Since a tenth of the total volume of pyroclastic debris is of juvenile origin, $2.5 \times 10^6 \text{ m}^3$ of basalt were involved in the eruptions. If large amounts of groundwater had not been available at depth beneath Hole-in-the-Ground, no phreatomagmatic eruptions would have taken place, and the rising basaltic magma would then have been poured out at the surface as lava or have been thrown out to build a cinder cone. The lava would be equivalent to a flow with an average thickness of 12.5 m. covering one square kilometer; an equivalent cinder cone with an average density of 2.0 would be 400 m. in diameter and 100 m. high. Higher up the slopes of the Paulina Mts., where less groundwater was available, only cinder cones and lava flows are to be found; in the Fort Rock basin and along

its margin, where groundwater was more abundant, maars and tuff-rings were developed.

Thorarinsson (1968) gives figures for the average rate of lava production during three recent eruptions in Iceland along fissures 4 m. wide and 100 m. long. The figures vary between 22 and 150 m³/sec., with a maximum production of 115 to 250 m³/sec. If a discharge of 20 to 100 m³/sec. along a fissure 100 m. long and one m. wide is assumed at Hole-in-the-Ground, the activity lasted between 2.6 and 13 days. Wright (1968) calculated a rate of 0.011 to 0.54×10^6 m³. lava/hrs. for the March 1965 eruption of Kilauea. If a rate of 0.05×10^6 m³. lava/hr. is applied at Hole-in-the-Ground, the eruptions lasted 18.7 days. Taking into account brief periods of repose, the activity may have lasted between a few days and a few weeks. The main eruptions that formed Nilahue maar in Chile in 1955 lasted about 10 days and activity ceased completely after another 3 months (Müller and Veyl, 1955).

Wentworth (1926) estimated the time taken to build the tuff-ring of Diamond Head, Oahu. In his opinion the volume of 0.6 km³ was discharged in 5 hours of cumulative eruption time. Taking into account periods of quiescence the tuff-ring could have been built in as much as 5 days. The subsurface volume of the tuff in the feeding structure was not taken into account.

A similar approach for the calculation of the discharge time for Hole-in-the-Ground can be made using 100 m./sec. as average discharge velocity, 0.04 g./cm³ as particle concentration of the eruption cloud, and a vent cross-section of 10⁴ m². The total amount of 4.5×10^{14} g. of pyroclastic debris involved would take 1.125×10^{14} sec. or nearly 3 hours and 10 minutes of discharge time. If periods of quiescence are taken into consideration the eruptions at Hole-in-the-Ground will also have lasted several days.

Summary of the History of Eruptive Activity

Between 13,500 and 18,000 years B.P., olivine basalt magma rose along a northwest-southeast trending fissure and began to vesiculate. About 40% of the magma had already crystallized when it came into contact with groundwater-saturated rocks at a depth of more than 300 m., and perhaps 500 m. below the surface. The groundwater-table at the time was at a depth of only 60 m. The top of the rising column of magma was consequently quenched to form sideromelane and was fractured, releasing its heat to vaporize abundant groundwater. Release of pressure led to rapid expansion of the vapor with consequent explosive eruption of shattered country rocks along with juvenile ejecta.

Repeated subsidence along a ring-fault led to repeated changes in groundwater supply and to repeated build-up of pressures at the eruption focus. Four times during the phreatomagmatic eruptions, orifice-pressures of 540 bars were reached, corresponding to ejection velocities of 200 m./sec. These four most violent eruptions may have been related to major stages of slumping or subsidence.

Ejecta were thrown to heights of 2 to 3 km. and to distances of nearly 4 km. The eruption clouds may have risen 5 km. or higher. The pattern of isopleths and isopachs indicates that no wind was blowing in the lower atmosphere and that the axis of eruption was slightly inclined toward the southeast. A few base surges rushed down the outer slopes of the crater rim, and large ejected blocks formed impact sags in the newly deposited wet pyroclastic debris.

The eruptions may have lasted several weeks. After they came to a close, groundwater filled the crater to the same height as the level of the adjacent Fort Rock Lake. The presence of this small crater lake, along with erosion, slumping, and subsidence account for redistribution of material on the walls and flat floor of the crater and removal of any inward-dipping tuffs of the rim.

COMPARLSON WITH OTHER CRATERS

The dimensions and shape of Hole-in-the-Ground fall within the range for maars computed from Noll's (1967) data (fig. 31), but Hole-in-the-Ground plots slightly off the diameter to depth curves given by Baldwin (1949) and Steinberg (1968). This could be the result of erosion which leads to a relatively small increase of the diameter and a more important decrease of the depth of a crater. Some modern maars, like Nilahue in Chile, Massem in northern Celebes, and Ubehebe in Death Valley, California, plot very close to the curve or even to the right of it. Hole-in-the-Ground, with a total energy of 5.7×10^{23} ergs, falls close to Baldwin's (1963, 1968) curve (fig. 32) for total energy vs. diameter for craters of various origins.

The similar size and age of Meteor Crater in Arizona and Hole-in-the-Ground make them appropriate for a comparison between a meteorite impact crater and a maar. Meteor Crater is a little over 1 km. in diameter and 200 m. deep (Shoemaker, 1962). The interior slopes are steeper than those of Hole-in-the-Ground which, along with a greater depth, gives Meteor Crater the appearance of being larger. The ratio of total energy expended vs. diameter is very similar for the two craters. The estimate of the total energy released at Meteor Crater is 3.4×10^{23} ergs (Baldwin, 1968),

remarkably close to that of Hole-in-the-Ground. The regional joint or fault pattern had more influence on the shape of Meteor Crater than on Hole-in-the-Ground, but the heights of the rims above the surrounding plains are very similar, 30-60 m. at Meteor Crater and 33-66 m. at Hole-in-the-Ground. In both places, shallow lakes formed in the crater soon after it formed and produced a flat floor.

Despite these similarities there are many dissimilarities that result from the different mechanisms of formation. At Meteor Crater the total amount of energy was spent in a single brief event, at Hole-in-the-Ground it was distributed over many events during a period of a few days or weeks. Small amounts of material were ejected at Hole-in-the-Ground during a single eruption, whereas the total ejected mass at Meteor Crater was thrown out in one single event.

The rim of Meteor Crater is uplifted, partly overturned, and cut by radial faults that have increasing displacements toward the center of the crater. Folding back and overturning of the brecciated rocks of the rim reverses their stratigraphic order and leaves them poorly stratified. Most blocks are angular and the largest have diameters of up to 30 m. (Shoemaker, 1962). The surface of the rim deposits is hummocky; the ejecta layer that contains a mixed breccia is not preserved on the rim but is found inside the crater. The ejected volume equals that of the crater. The ejected rocks show shock phenomena such as breccia zones, fractures and high-pressure phases.

In contrast, we see at Hole-in-the-Ground that the energy release was spread over a longer period of time; there is no raised rim but rather a

cleanly truncated one. All the components of the rim deposits are well mixed and stratified. The volume of the crater below the surrounding plain is only 60% of the volume of ejecta found outside the crater. Many of the larger blocks enclosed in the ejecta have been rounded by a milling process inside the vent. The maximum diameter of the largest blocks is only 8 m. (in contrast to 30 m. at Meteor Crater). Layering indicates multiple events and the block distribution points to pulses of relatively strong energy release. The surface of the ejecta blanket is smooth. Accretionary lapilli, sideromelane, impact sags with undisrupted bedding, and vesiculated tuffs indicate the availability of large amounts of ground water. Inrushing ground water may have supplied large amounts of water whereas at a meteorite impact crater only the ground water in the immediate sphere of influence of the impact may be involved in the ejection processes. At Hole-in-the-Ground the crater is underlain by a vent filled with pyroclastic debris the volume of which is greater than that of the breccia in the lens underlying Meteor Crater.

The geological features at both craters thus provide ample evidence for their different origin.

COMPARISON OF THE ERUPTIONS OF HOLE-IN-THE-GROUND WITH OTHER ERUPTIONS

The initial eruptions of the maar Nilahue in Chile, 27 July 1955 (Müller and Veyl, 1956), gave rise to ash clouds 7000 m. high and were accompanied by strong volcanic earthquakes up to magnitude four. The eruption of the maar Viti in northern Iceland on the 17th of May, 1724 also produced high ash clouds and strong quakes. It ejected blocks up to 1.5 m. in diameter (Noll, 1967).

The steam-blast eruption of Pematang Bata, Sumatra, in 1933 was preceded by a strong earthquake. Two maar-like craters were formed and clouds rose to elevations of more than 2000 m. The initial velocity of ejected material was approximately 147 m./sec. (Yokoyama, 1957).

Shimozuru (1968) determined the initial velocity of ejecta of a phreatic eruption of the Japanese volcano Aso in 1958 to be 96 m./sec. and estimated the kinetic energy of the ejecta as approximately 1.5×10^{19} ergs. The energy of accompanying volcanic earthquakes was of the order of only 10^{17} ergs.

Decker and Hadikusumo (1961) investigated the 12:14 January 16th, 1960 eruption of Anak Krakatoa which gave rise to a cloud 1000 m. high. For an individual explosion they found an initial velocity of ejecta of 77 m./sec., an orifice pressure of 74 atm., and kinetic energy of 6.4×10^{17} ergs. The energy of the accompanying seismic shock was only .02 percent of the kinetic energy of the eruption. Fries (1953) calculated an initial velocity of 95 m./sec. for blocks 10 cm. in size ejected during the May 27, 1945 eruption of Paricutin. Yokoyama (1957) gives initial velocities of 148 m./sec. for the eruption of Azumasa, Japan, in 1893, 170 m./sec. for Bandaisan in 1888, 193 m./sec. for Krakatoa in 1883 and 250 m./sec. for Asama, Japan, in 1783. More recent eruptions of Asama on 20 April 1935, 7 February 1936, 16 April 1937, and 7 June 1938 had initial velocities of 144.5, 130, 166.3, and 212.5 m./sec.

The strongest eruptions at Hole-in-the-Ground must have had initial velocities at least of 200 m./sec., orifice pressures of 540 bars, kinetic energy of the ejecta of about 9×10^{20} ergs, and accompanying seismic shocks of about magnitude five, the seismic energy being 0.6 percent of the kinetic energy. The strongest eruptions of Hole-in-the-Ground were comparable to some of the most powerful historic eruptions.

The strongest eruptions at Big Hole were even more powerful (Lorenz, 1970). The estimated values for that crater are 230 m./sec. for the initial fluid velocity, 715 bars for the orifice pressure, 1.33×10^{21} ergs for the kinetic energy, and a magnitude of approximately 5.15 for the accompanying seismic shocks. At Big Hole, however, the low fluid density of 0.01 g./cm^3 resulted in a smaller equilibrium size for ejecta of 7.5 m. At Hole-in-the-Ground the fluid density was about 0.04 g./cm^3 and the equilibrium size was 23 m. The largest block found at Big Hole consequently measures only 2.3 m. across whereas at Hole-in-the-Ground it measures 8 m. across. The difference in fluid density may reflect variations in the diameter of the vents and crater, variations in the amount of gas and solid phase available, and different parameters of the gas phase.

Richards (1965) studied the relationship between orifice pressure and the kinetic energy of ejecta and found that it was linear. If the assumed values for the strongest eruptions at Hole-in-the-Ground and Big Hole are plotted on the diagram (fig. 33) Richards derived from the four eruptions of the volcano Asama, Japan and one eruption of Bezymianny in Kamchatka, Big Hole plots nearly on the curve, whereas Hole-in-the-Ground does not. For the same pressure the kinetic energy of the strongest eruption of Hole-in-the-Ground would have to be only one-third of the calculated one. In as much as Richards' curve is based on only five eruptions and that our calculation of the kinetic energy for Hole-in-the-Ground is based on an uncertain value for the ejected mass, it is not surprising that agreement is less than perfect.

At the Pinacate maars in Sonora, Mexico, the largest blocks found in the otherwise fine-grained pyroclastic debris measure 6 m. across (Jahns, 1959).

Blocks of 3 m. diameter are found at the Puebla maar in Mexico (Shoemaker, 1962). At the Graenavatn maar in Iceland, which is only 340 to 260 m. in diameter, the largest blocks on the rim have a diameter of 4.0 m. (Noll, 1967).

McGetchin (1966) showed in his detailed study of Moses Rock diatreme, Utah, that the equilibrium size of blocks in the pipe was about 30 m. at a depth of 1000 m. below the original surface. At Hole-in-the-Ground the equilibrium size at the crater was calculated as approximately 23 m. It is not yet known, however, how the equilibrium size varies with fluid parameters and depth.

Thus recent as well as some older eruptions that produced maars testify to very violent events, explosions and strong earthquakes, but much remains to be learned about the complex relationships of gas pressures, ejection velocities and the size of ejected blocks.

COMPARISON OF THE BLOCK DISTRIBUTIONS FROM THE ERUPTIONS

AT ASAMA, JAPAN, AND HOLE-IN-THE-GROUND

The block distributions of four eruptions of volcano Asama from 1935 to 1938 were studied by Minakami (1941) who found that blocks of different size left the crater with the same initial velocity but that the velocities were different for each eruption. In contrast, we find at Hole-in-the-Ground that blocks of different size seem to have left the crater with different initial velocities, the larger blocks being slower than the smaller ones.

The block distribution at Asama indicates that the blocks did not receive their initial acceleration from a higher velocity gas-solid stream.

It may be more reasonable to assume that plugflow of the type observed in fluidization experiments was responsible for the block distribution. During the 1937 eruption of Asama the orifice had a diameter of only 50 m. This relatively small diameter would favor plugflow, because at a small ratio of diameter to depth of a vent the expanding gas phase tends to push a mass of fragmentary material or viscous magma ahead of itself. This mass then behaves nearly as a single unit within the upper part of the vent until it is no longer restricted by the vent walls and begins to break up into individual fragments each having nearly the same velocity.

Another factor that seems to favor the plugflow model is the fact that the Asama eruptions had a short duration. When the plug of solid or viscous material was lifted and pressure was released the system returned to a "non-explosive" condition.

The differential velocities of the blocks of different size at Hole-in-the-Ground are evidence that plugflow was not important in the upper part of the vent during the eruptions that formed the main horizons. If there was plugflow transport in the lower part of the vent, the plug must have disintegrated to allow adjustment of the velocities of individual blocks to a dense gas-solid system in the upper part of the vent.

The 1968 eruption of volcano Arenal in Costa Rica seems to be another example of plugflow. During that eruption blocks of different size landed more than 4 km. from the crater (Minakami and Utibori, 1969). It may be significant in this respect that both Asama and Arenal are andesitic volcanoes. In a narrow conduit the cool and viscous top of the magma column may function as a plug and thus give rise to the block distributions described by Minakami.

Sakuma and Nagata (1957) state that initial velocities of large blocks of more than 100 m./sec. cannot be considered as due to gas transport but are the result of the accelerating impulse of suddenly expanding high pressure gases. If only the gas-phase is considered for transport of the large blocks at Hole-in-the-Ground, unreasonably high velocities are required to eject these blocks. On the other hand, a dense gas-particle system, such as that postulated for Big Hole or Hole-in-the-Ground, where large volumes of the dense two-phase systems transported relatively small volumes of large blocks would require velocities of only 100 to 300 m./sec.

Acknowledgments

The author wishes to express his thanks to Dr. Alexander R. McBirney and Dr. Howel Williams for valuable discussions and extensive editing of the manuscript. Discussions concerning aspects of fluidization were held with Drs. H. A. Einstein, R. I. Pigford, and Th. Vermeulen at the University of California, Berkeley. Chong Kim, who had written a thesis on geophysical aspects of Hole-in-the-Ground, provided a better understanding of the subsurface structure. Stephen Bedwell provided the results of his anthropological studies on the early inhabitation of the Fort Rock area. Mr. Richard Freeman and John Petruskiewics assisted in digging test pits at Hole-in-the-Ground. Official of the United States Forest Service, Deschutes National Forest, especially Mr. H. McCormick and E. Slonecker, gave permission to improve the road into Hole-in-the-Ground and to drill two deep holes inside the crater. Mrs. Jeannie Heer and Linda Purvis typed the manuscript.

The project was supported by NASA Grant NGR-38-003-012 to A. R. McBirney, principal investigator.

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